UNANSWERED QUESTIONS IN NEUTRINO SCATTERING

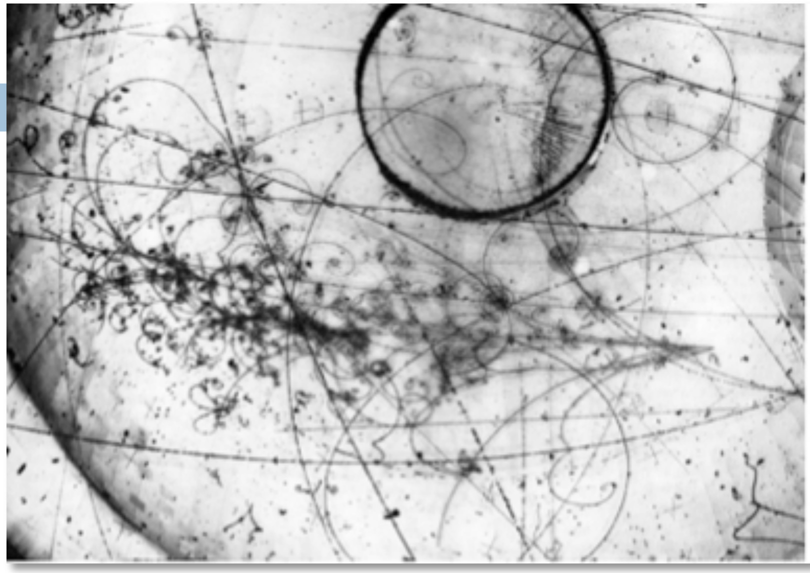
Sam Zeller
Fermilab

Penn seminar

April 17, 2012

• a topic that we really haven't talked about in a really long time and one that has gotten a lot more interesting over the past year

Introduction



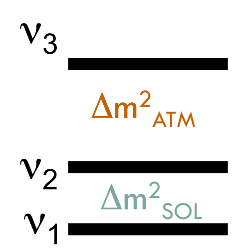
- physicists have been scattering neutrinos off nuclei for decades
- so why so much interest in this topic now?

- *the study of ν oscillations over the past 15 years has certainly placed new demands on our understanding of ν interactions*
- *the availability of modern, very intense ν sources has provided an excellent opportunity to revisit this physics, decades later*
- *like any measurement, new data and higher statistics explorations can reveal previously hidden subtleties and raise new questions*

Neutrino Physics

- looking forward, there are some big questions we will be trying to answer
- next generation of experiments will largely be focused on answering several key questions:

- what are the masses of neutrinos?
- are neutrinos their own anti-particles?
- is there a 4th neutrino?
- is θ_{13} non-zero?
- what is the ν mass ordering?
- is CP violated in the ν sector?

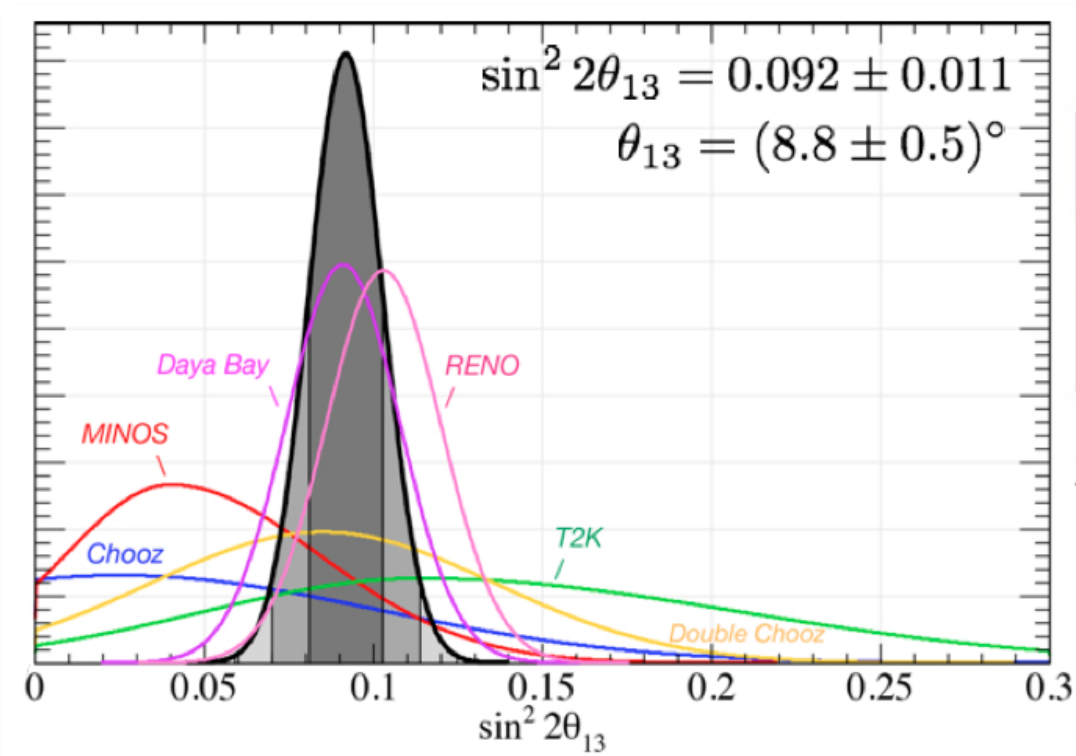


Big Question

Do you know what θ_{13} is yet?

The New θ_{13} Landscape

… looks something like this:



(M. Messier)

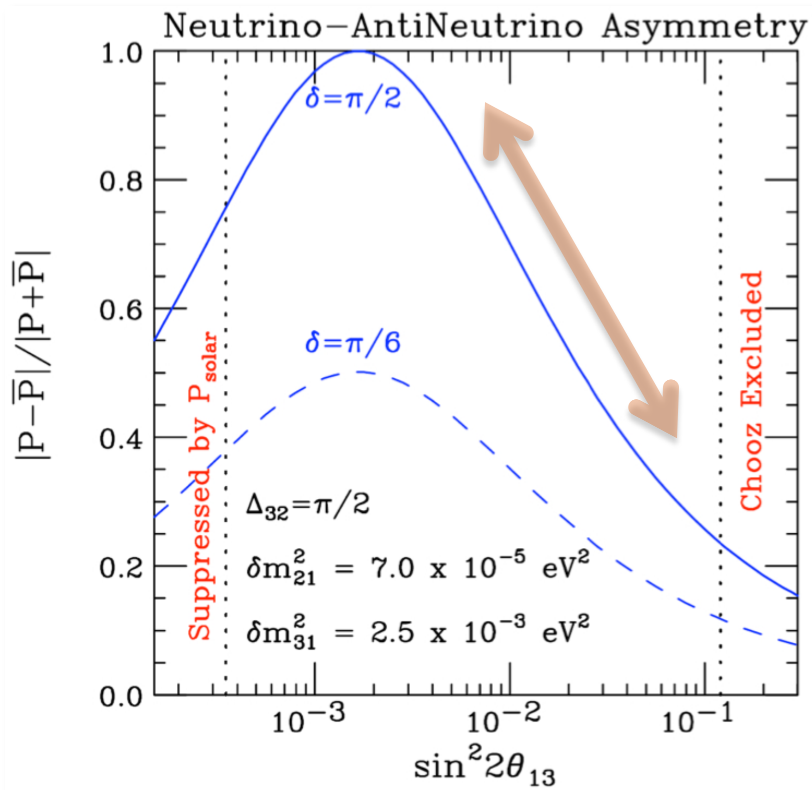
- θ_{13} is the gate-keeper
- it's large value opens up new windows of opportunity because it allows for measurable matter effects (MH) and opens the door for measuring CP violation in the ν sector
- "signal is now guaranteed and measurement of δ_{CP} is guaranteed"

What Does Large θ_{13} Mean?

- we'll enjoy larger signal samples
- can determine the MH more quickly

What Does Large θ_{13} Mean?

(S. Parke)



- we'll enjoy larger signal samples
- can determine the MH more quickly
- but it doesn't mean that the CP measurement is any easier
  - the $\nu/\bar{\nu}$ asymmetry is smaller as θ_{13} gets larger
  - systematics start to become increasingly important

- places even greater demands on our knowledge of ν (& $\bar{\nu}$) interactions

Neutrino Cross Sections

- to address MH and $\not{C}\not{P}$, are going to even longer baselines

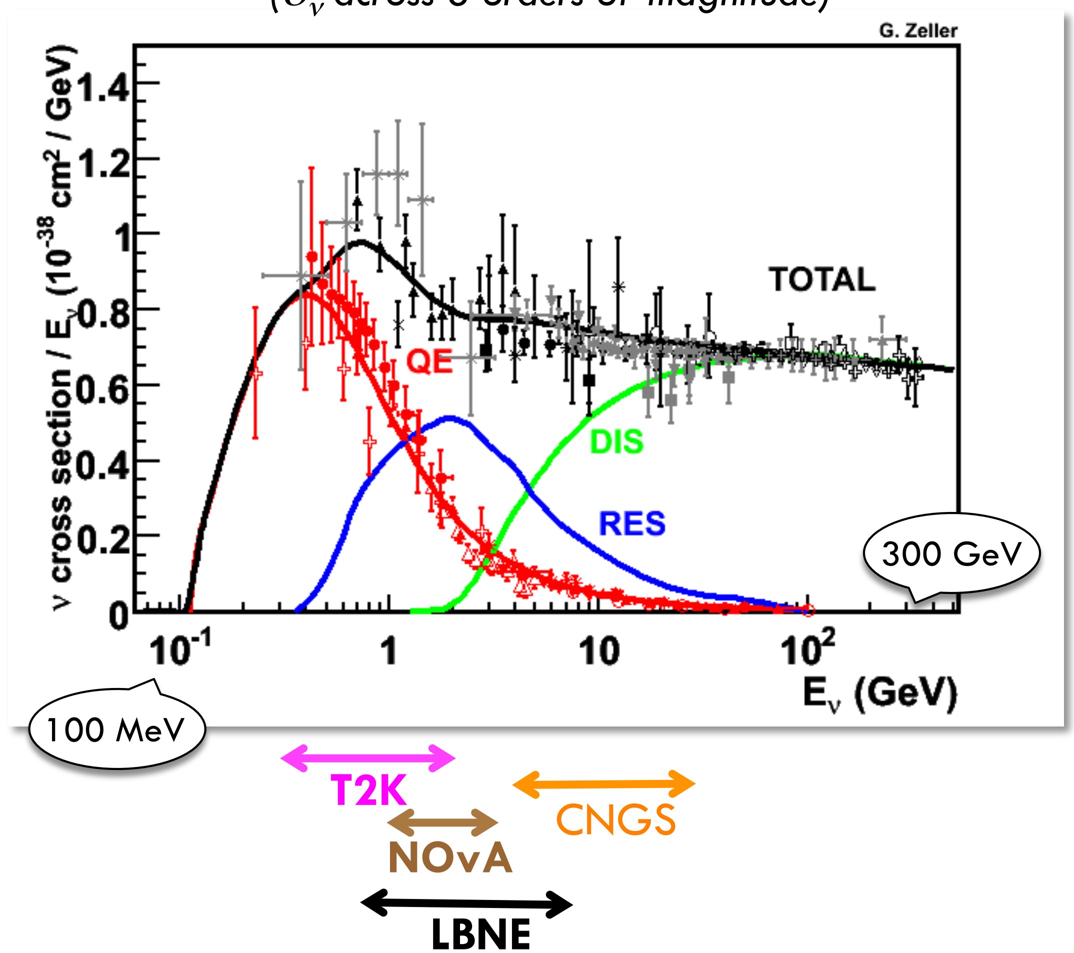
implies E_ν's of a few-GeV to be sensitive to these effects

- this region is dominated by poorly known ν cross sections

- this region is complex (lots of rich physics here)

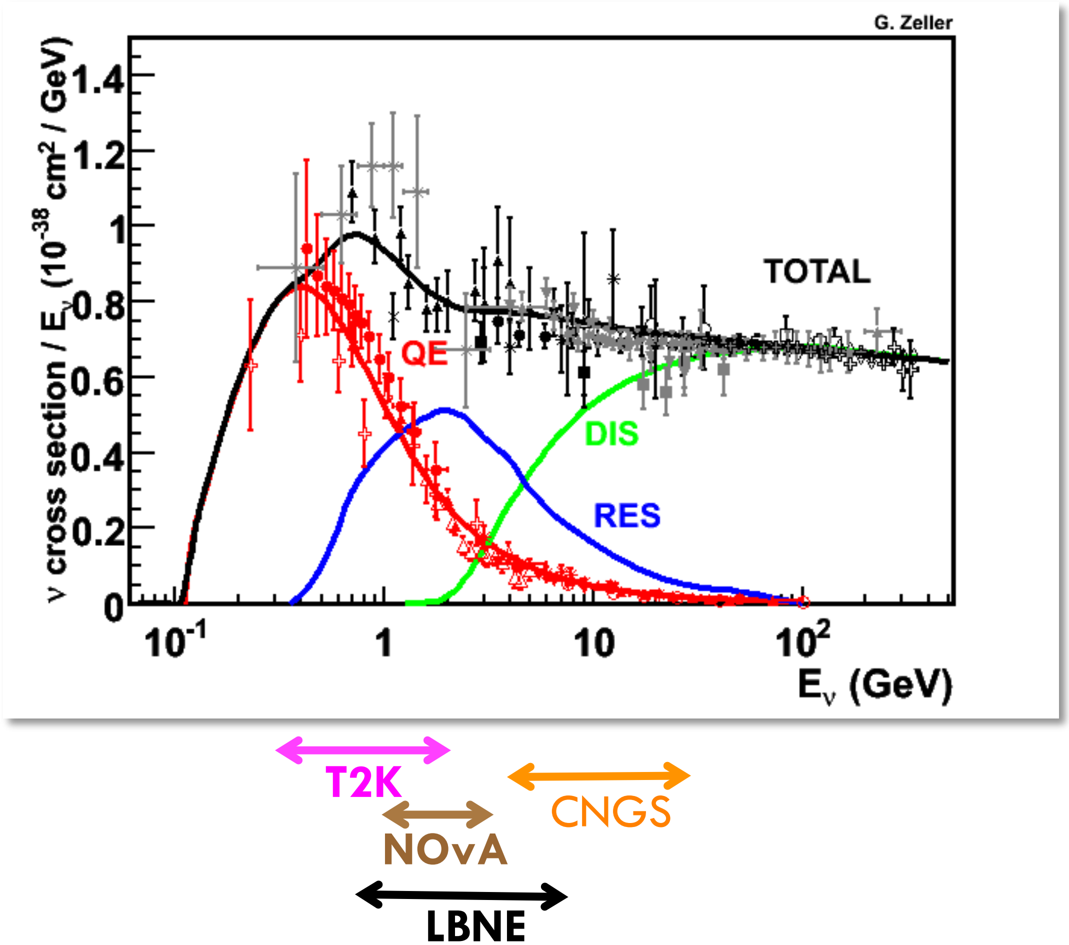
- challenges:
  - sizable nuclear effects
  - multiple σ contributions

(σ_ν across 3 orders of magnitude)



Why Is This Complicated?

three basic reaction processes:



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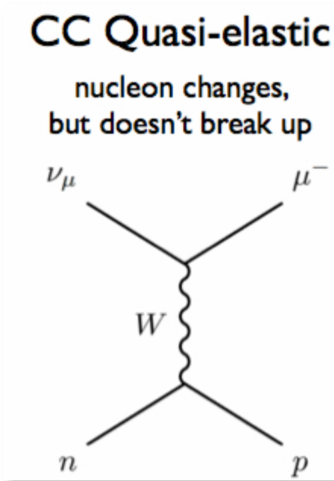
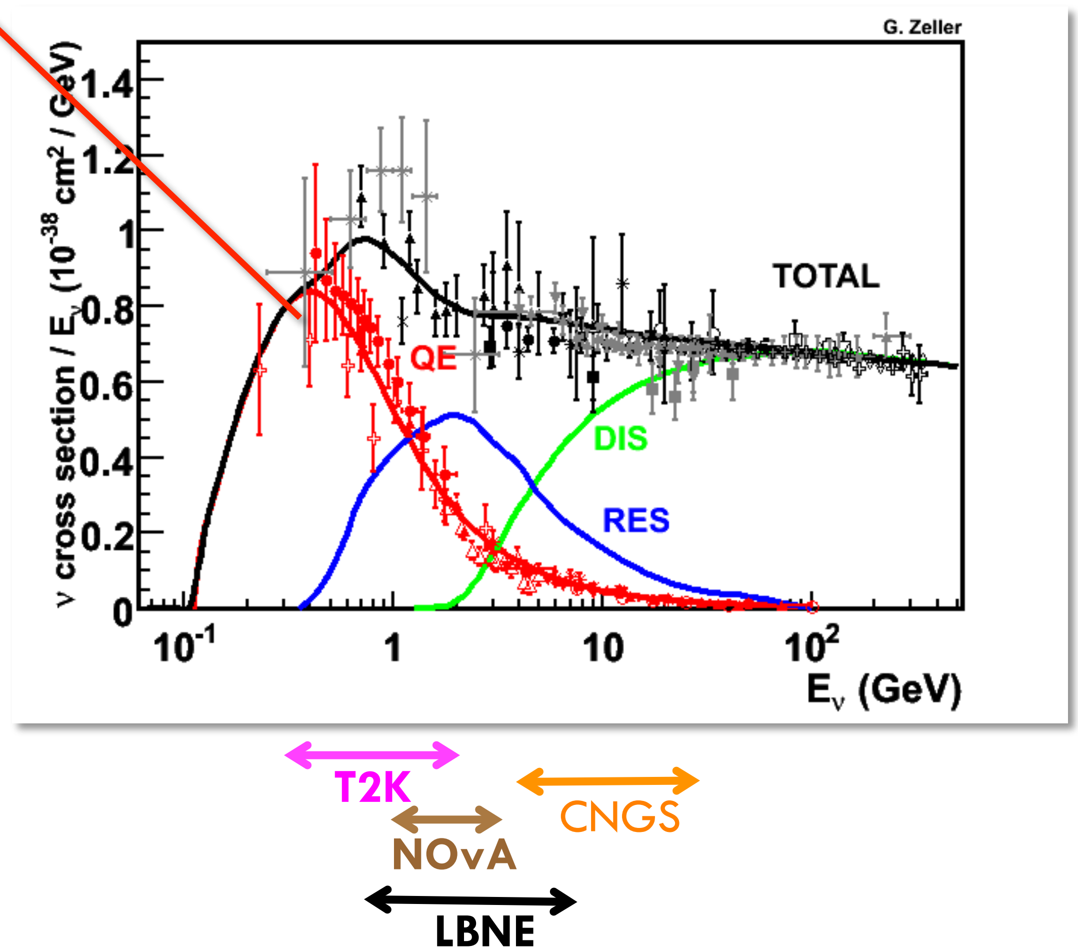


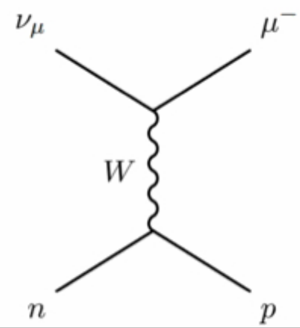


Why Is This Complicated?

three basic reaction processes:

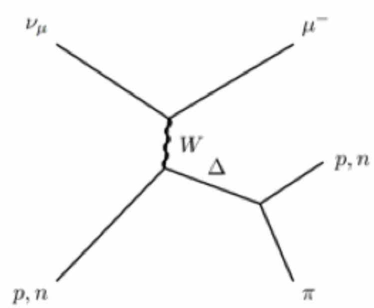
CC Quasi-elastic

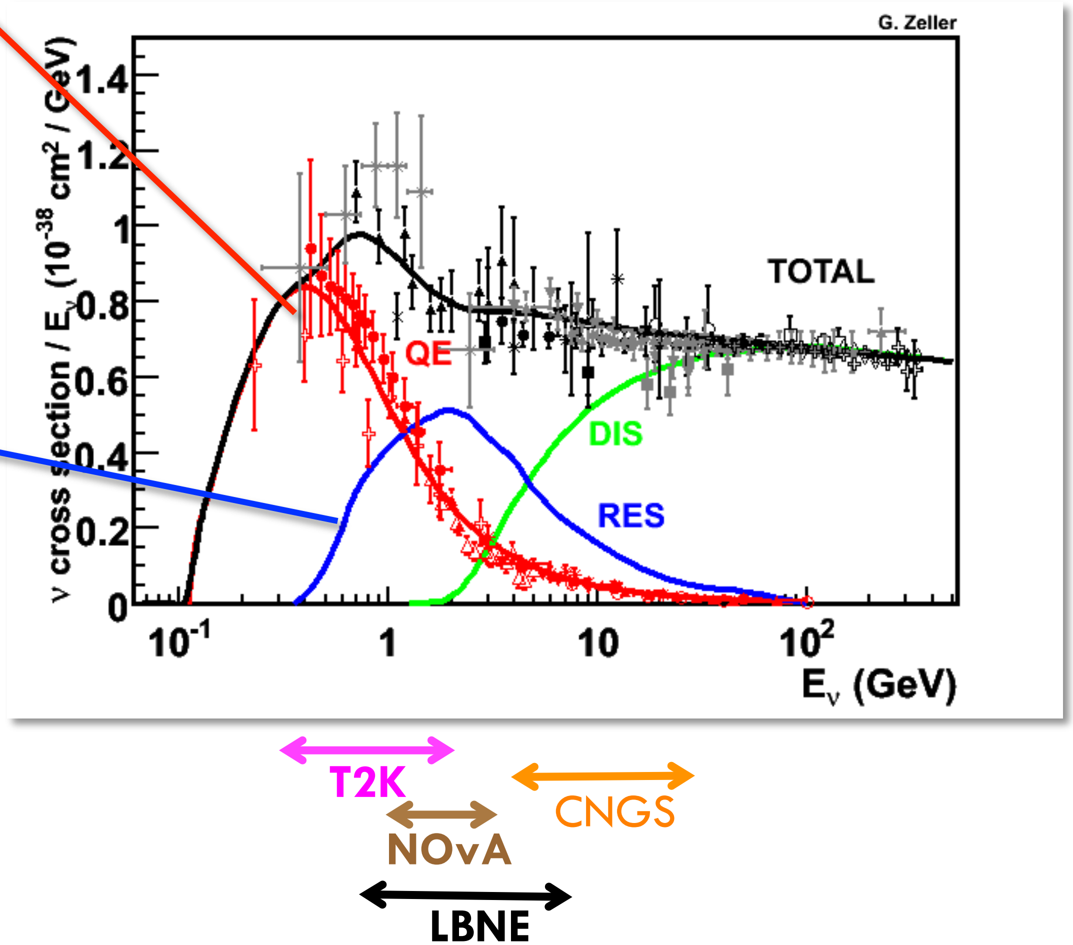
nucleon changes, but doesn't break up



CC Single pion

nucleon excites to resonance state





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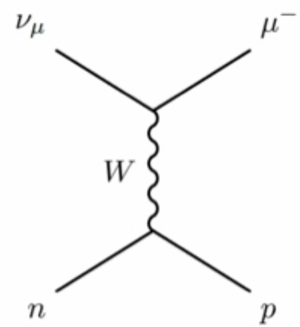

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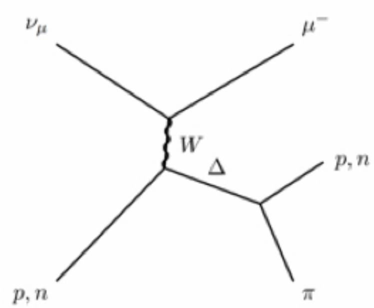
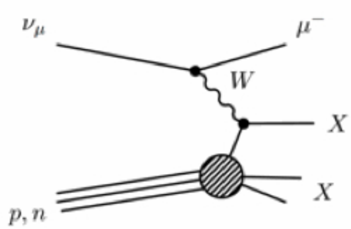
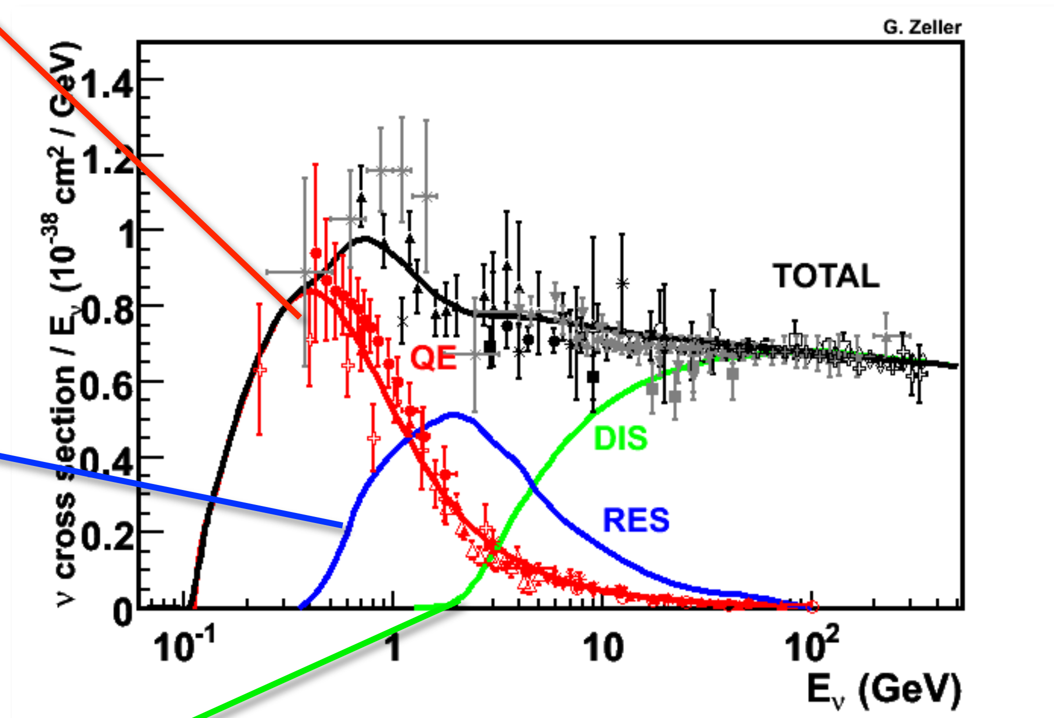


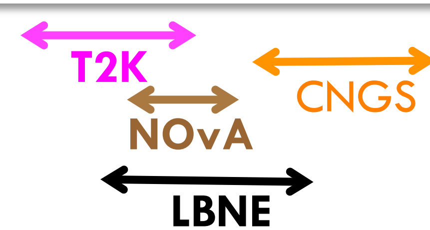
CC Deep Inelastic

nucleon breaks up



(accel-based ν experiments all use broad band beams, so contain contribs from all of these reaction mechanisms)





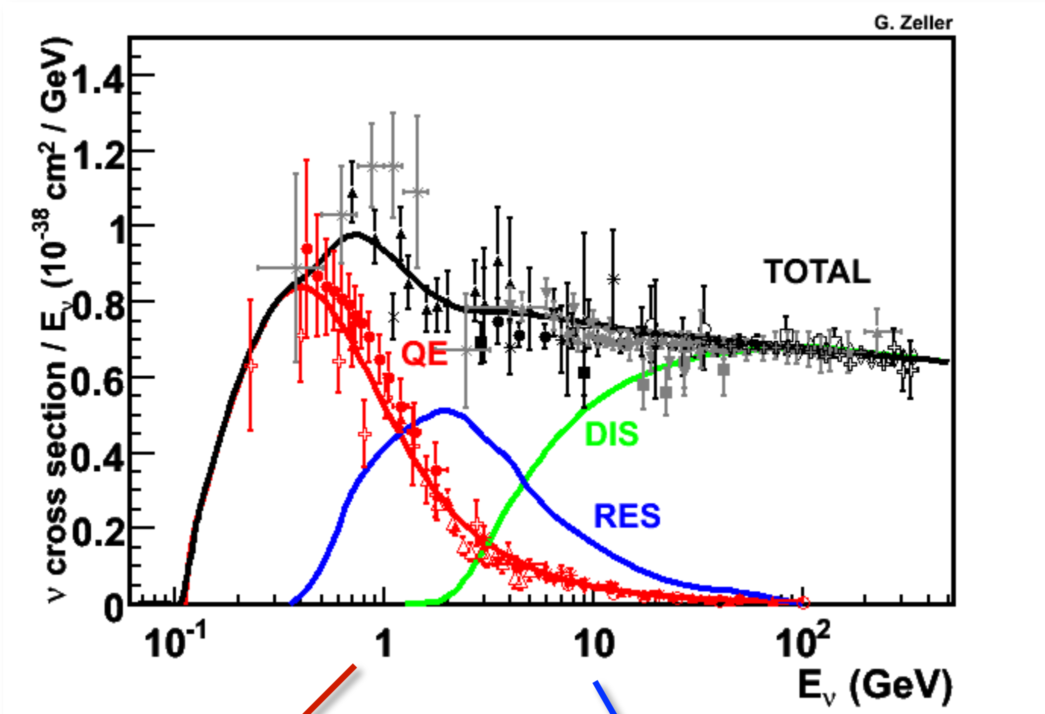
Experimental Data

- most of our information comes from data that is > 30 years old

(data you see on this plot, low stats but crucial for establishing overall size of σ, mostly D_2, H_2)

- good news: modern exps are making improved σ_ν measurements

- <u>advantages of new data:</u>
  - *higher statistics*
  - *intense, well-known ν beams*
  - *nuclear targets (crucial!)*



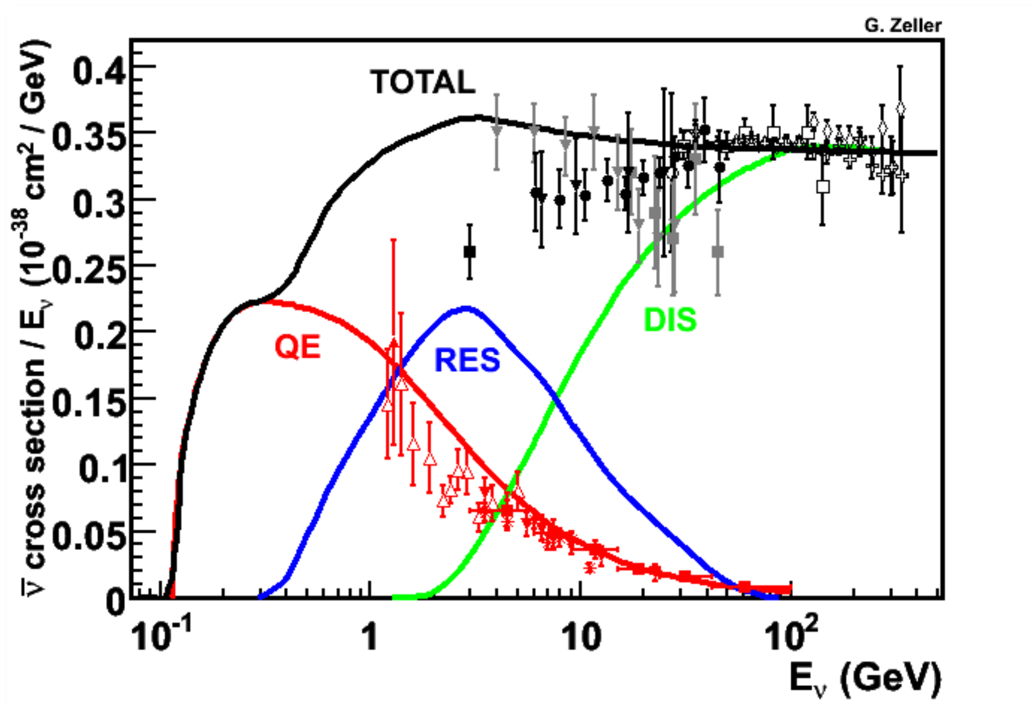
K2K, **MiniBooNE**, MicroBooNE, SciBooNE, T2K

ArgoNeuT, ICARUS, MINERνA, MINOS, NOMAD, NOvA

And Oh By The Way …

- need to know all of this for antineutrinos too!
  (will be important for ~~CP~~)

- existing measurements are even more sparse in this case



- recognizing that "every problem is an opportunity in disguise", MiniBooNE launched a rather extensive neutrino cross section program

MiniBooNE Experiment

- MiniBooNE designed and built to study neutrino oscillations ($\nu_\mu \rightarrow \nu_e$ at large Δm^2 to address LSND)

small collaboration
~74 physicists, 18 institutions

MiniBooNE Experiment

- MiniBooNE designed and built to study neutrino oscillations ($\nu_\mu \rightarrow \nu_e$ at large Δm^2 to address LSND)

- have been running for ~10 yrs now

Event Excess in the MiniBooNE Search for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ Oscillations

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(The MiniBooNE Collaboration)

[1]*University of Alabama; Tuscaloosa, AL 35487*
[2]*Argonne National Laboratory; Argonne, IL 60439*
[3]*University of Cincinnati; Cincinnati, OH 45221*
[4]*University of Colorado; Boulder, CO 80309*
[5]*Columbia University; New York, NY 10027*
[6]*Fermi National Accelerator Laboratory; Batavia, IL 60510*
[7]*University of Florida; Gainesville, FL 32611*
[8]*Indiana University; Bloomington, IN 47405*
[9]*Los Alamos National Laboratory; Los Alamos, NM 87545*
[10]*Louisiana State University; Baton Rouge, LA 70803*
[11]*Massachusetts Institute of Technology; Cambridge, MA 02139*
[12]*Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México, D.F. 04510, México*
[13]*University of Michigan; Ann Arbor, MI 48109*
[14]*Saint Mary's University of Minnesota; Winona, MN 55987*
[15]*Yale University; New Haven, CT 06520*

(Dated: September 15, 2010)

The MiniBooNE experiment at Fermilab reports results from a search for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations, using a data sample corresponding to 5.66×10^{20} protons on target. An excess of 20.9 ± 14.0 events is observed in the energy range $475 < E_\nu^{QE} < 1250$ MeV, which, when constrained by the observed $\bar{\nu}_\mu$ events, has a probability for consistency with the background-only hypothesis of 0.5%. On the other hand, fitting for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations, the best-fit point has a χ^2-probability of 8.7%. The data are consistent with $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations in the 0.1 to 1.0 eV^2 Δm^2 range and with the evidence for antineutrino oscillations from the Liquid Scintillator Neutrino Detector at Los Alamos National Laboratory.

Aguilar-Arevalo *et al.*, PRL **105**, 181801 (2010)

MiniBooNE Experiment

- MiniBooNE designed and built to study neutrino oscillations ($\nu_\mu \rightarrow \nu_e$ at large Δm^2 to address LSND)

- have been running for ~10 yrs now

- over a million neutrino & antineutrino interactions!

  (world's largest data set in this E range; we quickly realized there were potentially some useful measurements to be made here)

- σ_ν are a big part of our program

- have since measured σ's for ~90% of ν events in MB *(high statistics, high quality data)*; turning out to be more interesting than we thought!

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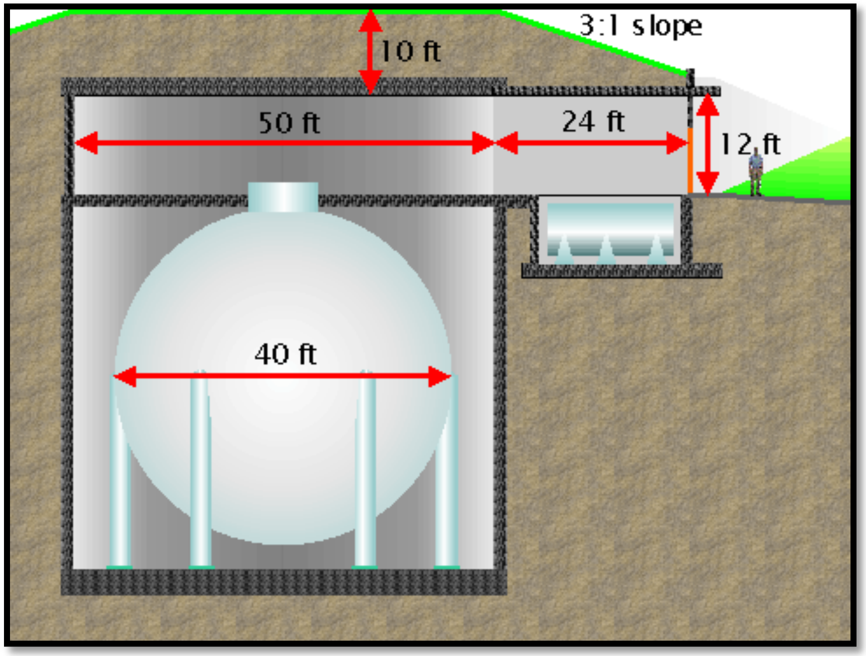
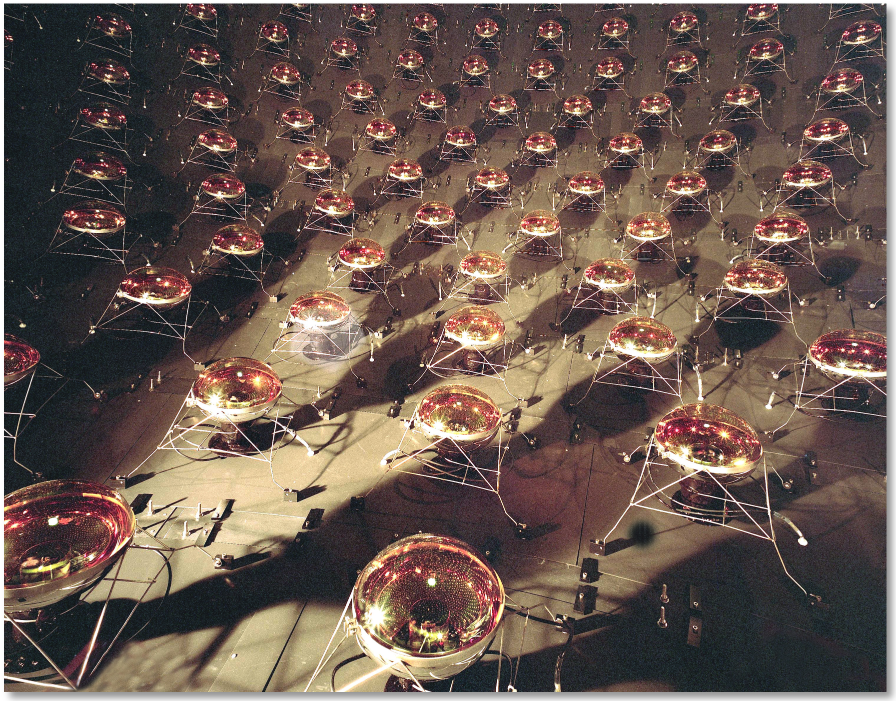
MiniBooNE Detector

Aguilar-Arevalo *et al.*, NIM **A599**, 28 (2009)



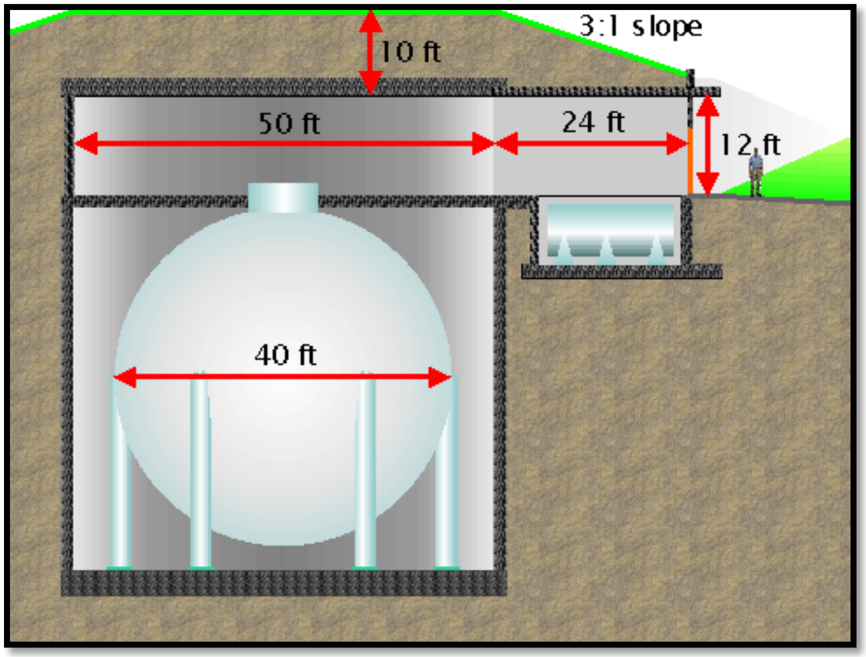


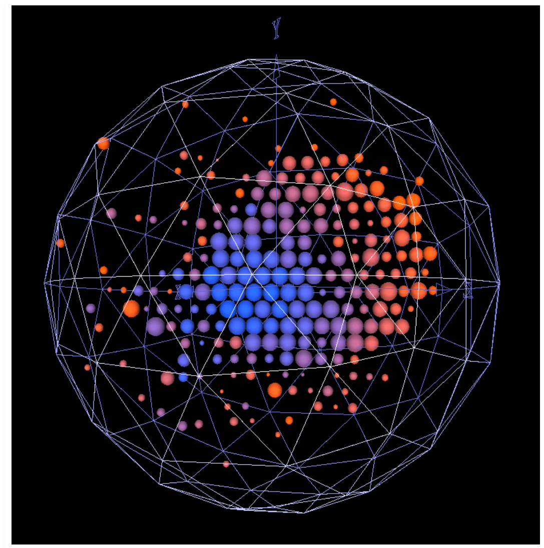
(inside view of MB tank)

- 800 tons of mineral oil
- ν interactions on CH_2
- Čerenkov detector → ring imaging for event reconstruction and PID

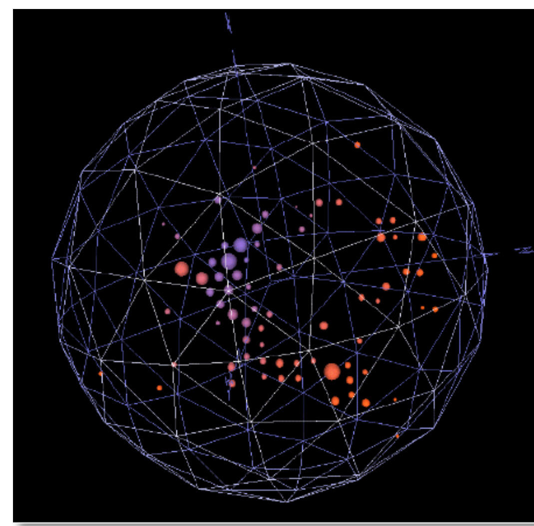
MiniBooNE Detector

Aguilar-Arevalo *et al.*, NIM **A599**, 28 (2009)





muon candidate



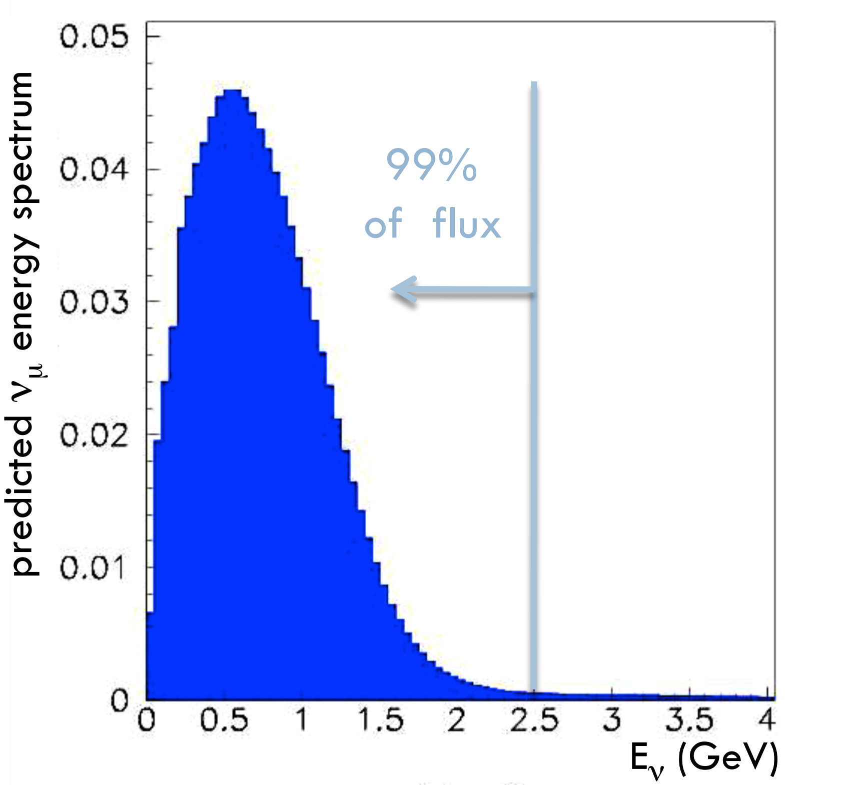
electron candidate

based on Č ring topology, can differentiate different particle types

- 800 tons of mineral oil
- ν interactions on CH_2
- Čerenkov detector → ring imaging

Neutrino Flux

flux of neutrinos seen by the detector:



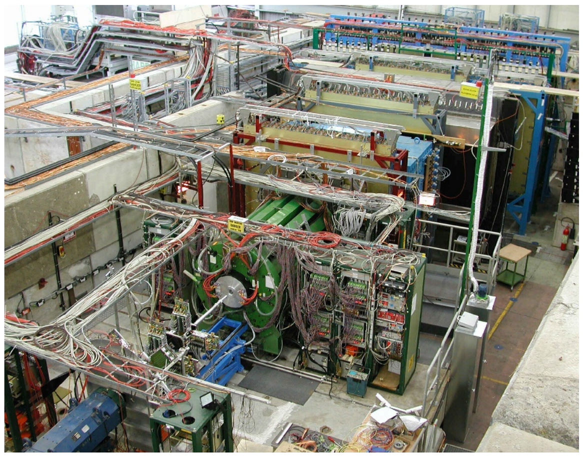
- MB operates in the Booster ν beamline at Fermilab
- ν and $\bar{\nu}$ (currently $\bar{\nu}$)
- well-suited for low energy ν cross section studies

  $\langle E_\nu \rangle \sim 0.8$ GeV

  - enjoy small backgrounds from higher multiplicity ν interactions

    (perfect for QE + RES !)
- relevant to LBL ν oscillation experiments (T2K, NOvA, LBNE)

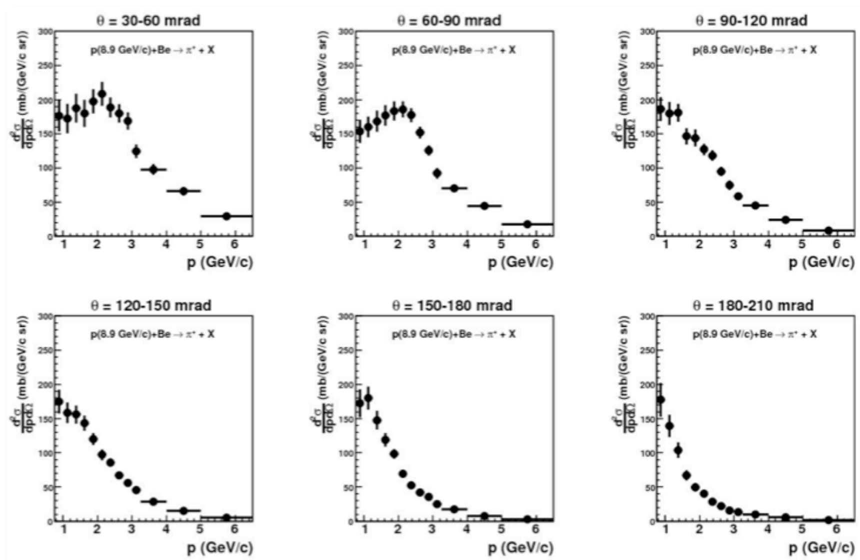
Flux Prediction



- made dedicated hadro-production measurements at CERN specifically for MiniBooNE

M. Catanesi *et al.*, Eur. Phys. J. **C52**, 29 (2007)

- same beam energy
- exact replica target



(D. Schmitz, Columbia, Ph.D. thesis)

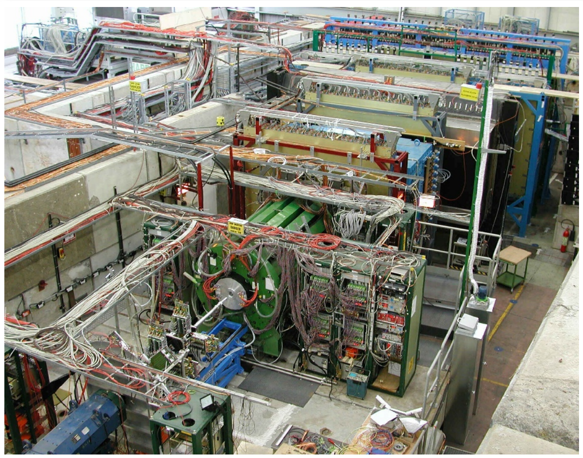
- need to know your ν flux to make ν cross section measurements

- comprehensive ν flux paper

Aguilar-Arevalo *et al.*, PRD **79**, 072002 (2009)

- there was no tuning of flux based on MiniBooNE ν data!

Flux Prediction



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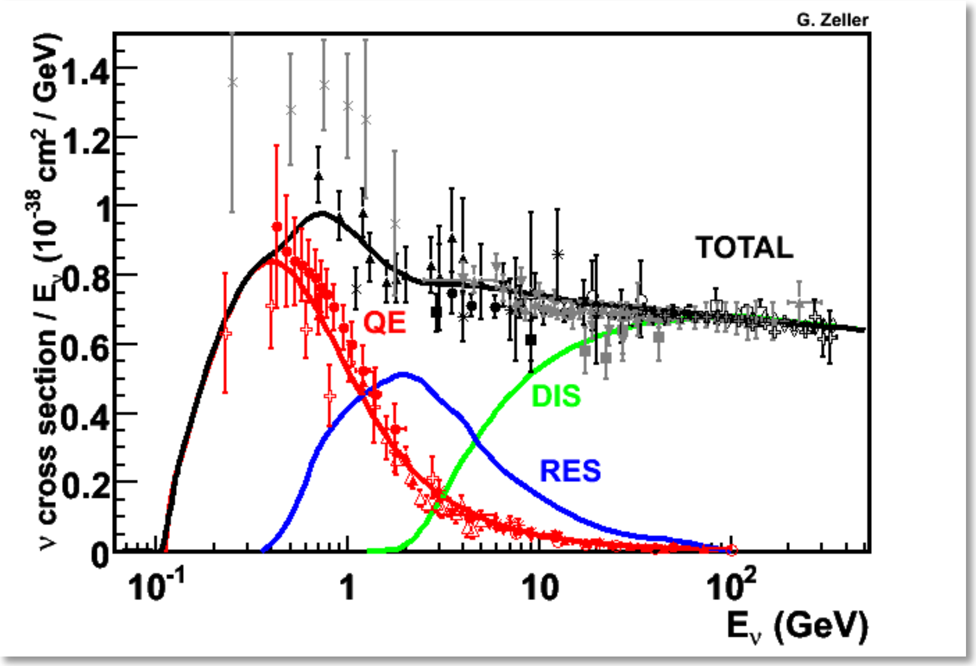
> To obtain the total cross section from the number of events, the neutrino flux has to be measured on an absolute scale. In this analysis, we determine the neutrino flux using 362 quasielastic events identified in our data[10] and the cross section for reaction (2) derived from the $V-A$ theory.

Phys. Rev. D23, 11 (1981)

Neutrino Interactions

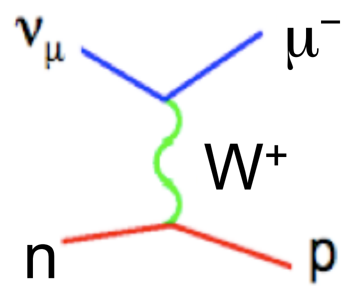
- we'll use this plot as our guide as we survey the landscape

- let's start on the left and work our way up in energy …



- what have we learned in exploring this region again 30+ years later?

Quasi-Elastic Scattering



(one of the most basic ν interactions, single knock-out nucleon)

Why important?

- **important for ν oscillation experiments**
  - typically gives largest contribution to signal samples in many osc exps

signal events

examples:

$\nu_\mu \rightarrow \nu_e$ (ν_e appearance)

$\nu_\mu \rightarrow \nu_X$ (ν_μ disappearance)

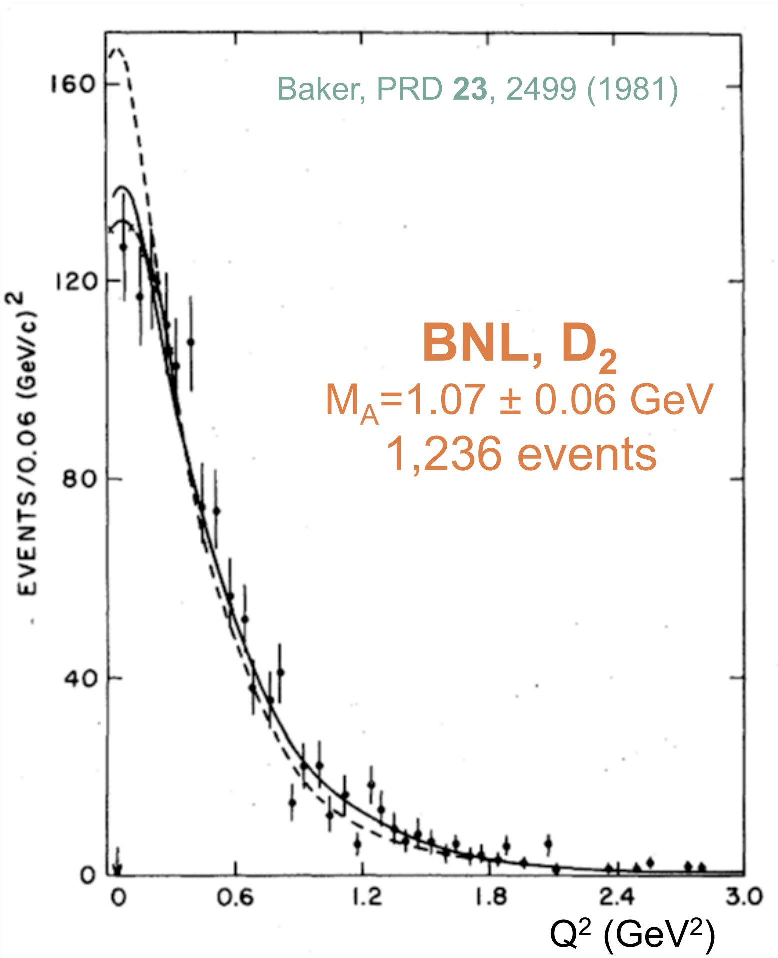
- biggest piece of the σ at ~1 GeV

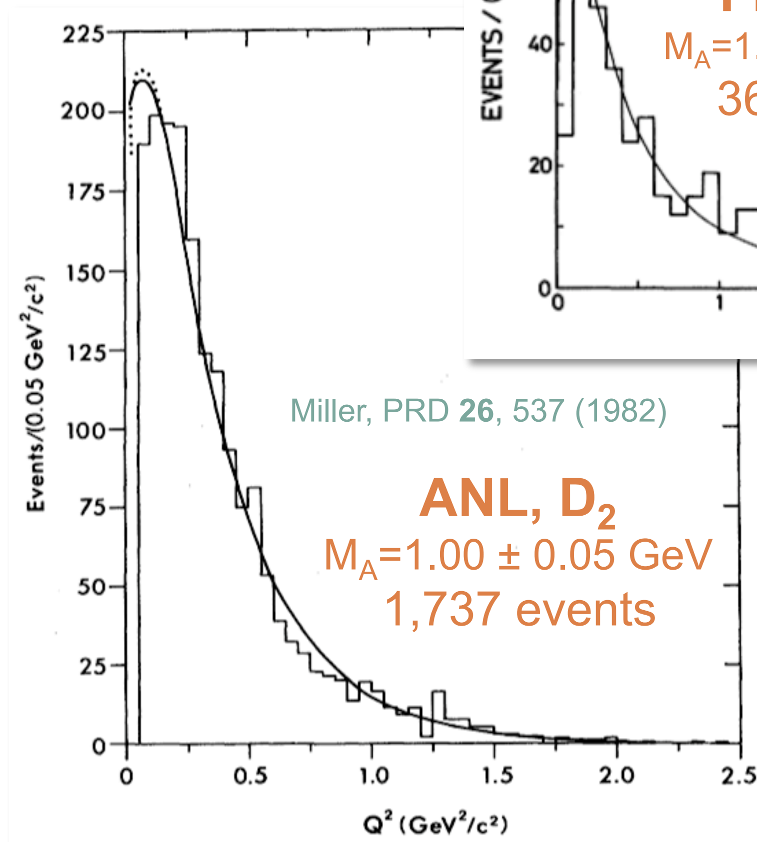
(lepton kinematics are used to infer E_ν)

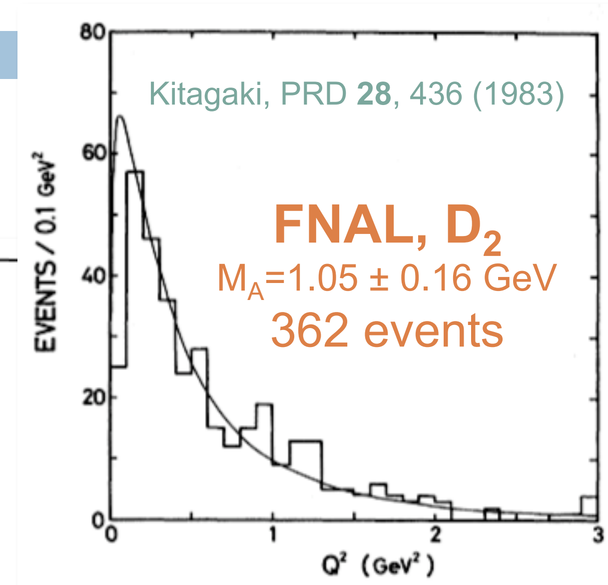
(heavily studied in 1970's and 80's, one of the 1st ν interactions measured)

Past Examples

$\nu_\mu\, n \rightarrow \mu^-\, p$







goal: make more accurate predictions for NC, so measured the axial FF in CC scattering

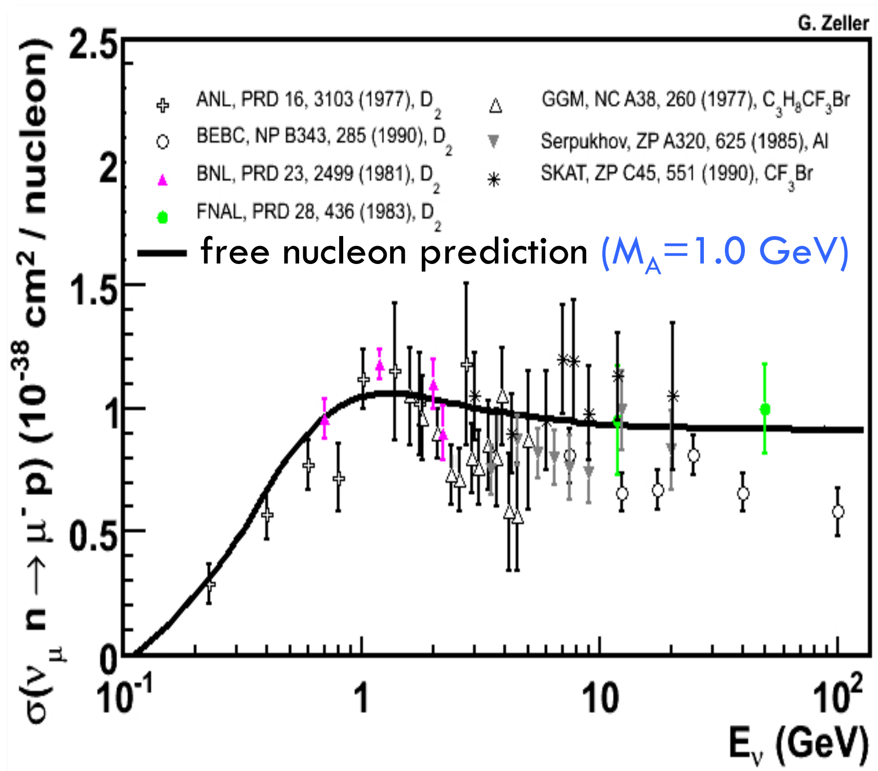
- focus of many early bubble chamber exps (D_2) $\Longrightarrow$ $M_A \sim 1.0$ GeV

QE Cross Section

- these same exps also measured $\sigma(E_\nu)$

$\nu_\mu\, n \rightarrow \mu^-\, p$

- conventional wisdom has always been that **this σ is well-known**
  - *it's a simple 2-body process*
  - *basic picture is that ν interacts with one nucleon at time*
- this description has been quite successful
  - *can predict size, shape of σ*
- can consistently describe all the experimental data
  - *most is on D_2*
  - *M_A=1.0 GeV*



with these ingredients, it looked straightforward to extend this to describe ν QE scattering on nuclei

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$\nu_\mu\, n \rightarrow \mu^-\, p$

Fermi Gas Model

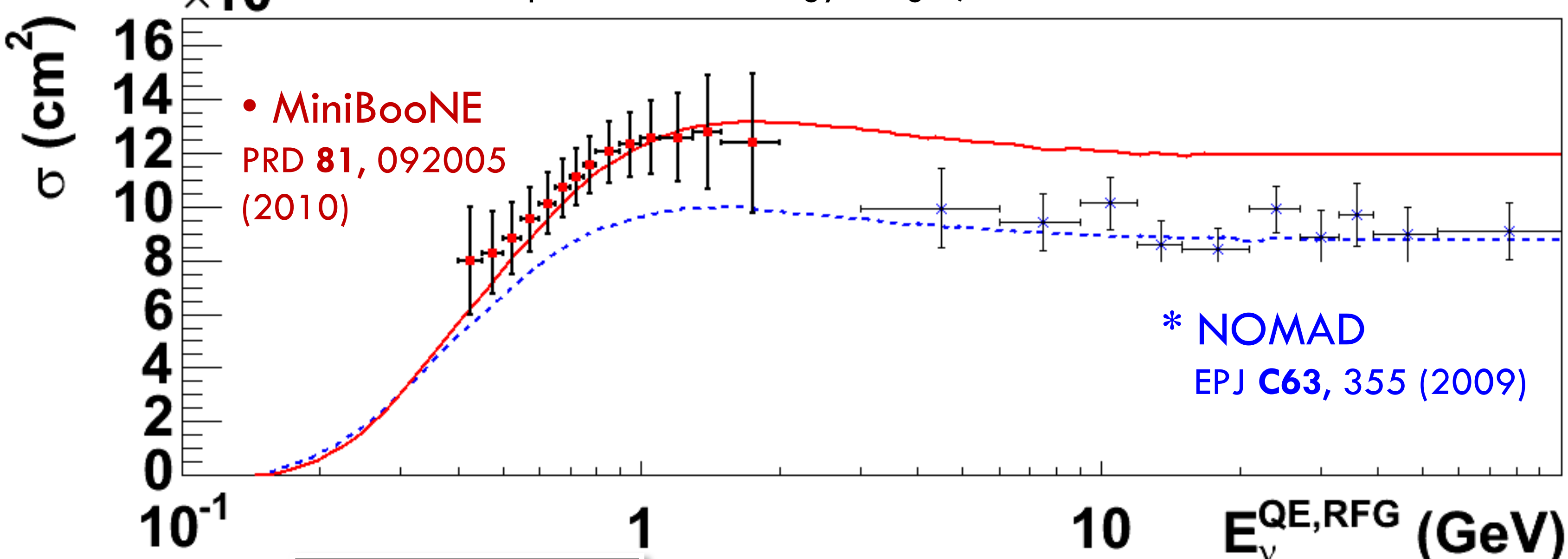
(heavily used today)

scattering off a collection of independent nucleons in the nucleus

QE Cross Section on Carbon

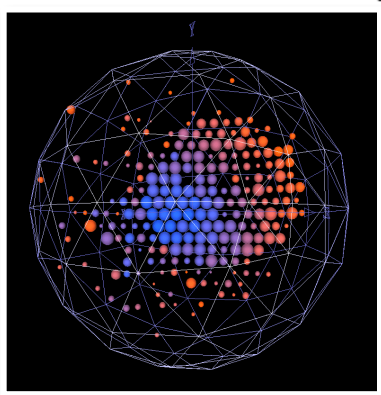
- repeated 30 years later … this time on carbon

two exps: different energy ranges, different detectors … different detection



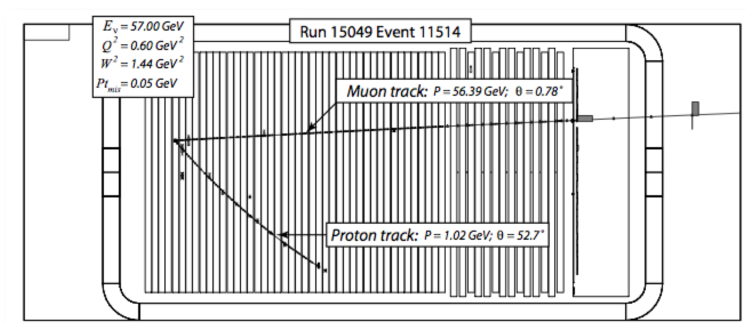
MiniBooNE (FNAL) 2002-present

relies on μ reconstruction

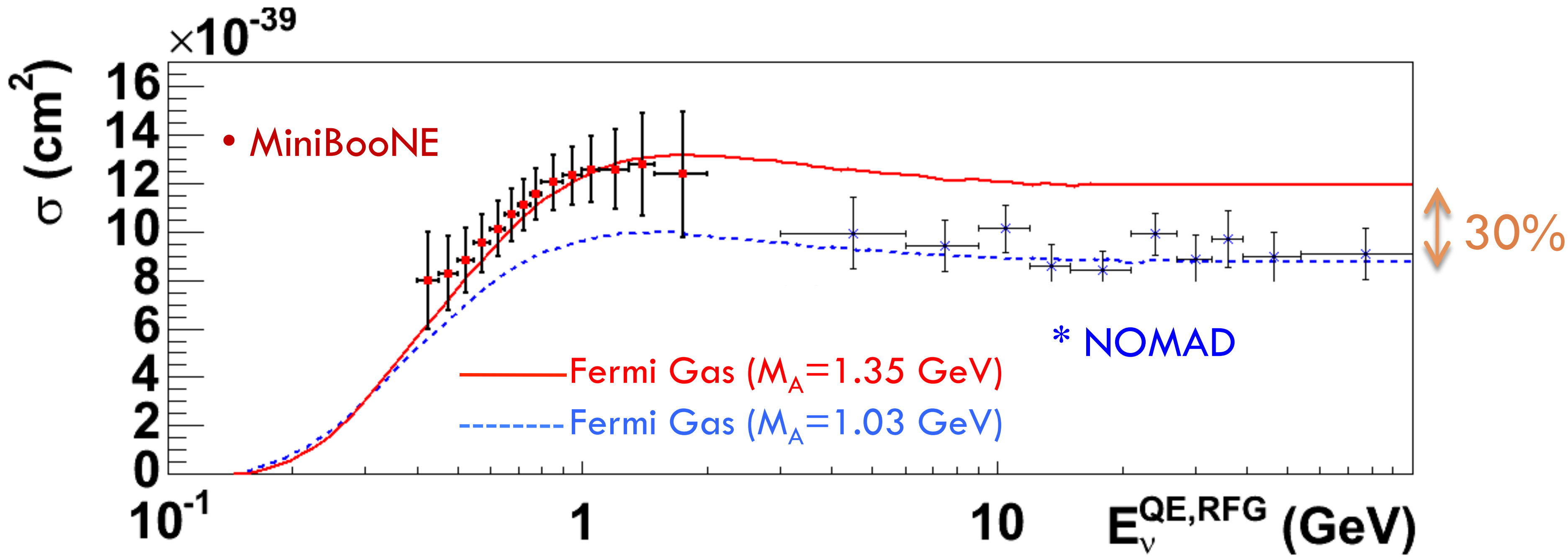


NOMAD (CERN) 1995-1998

sees both μ and proton

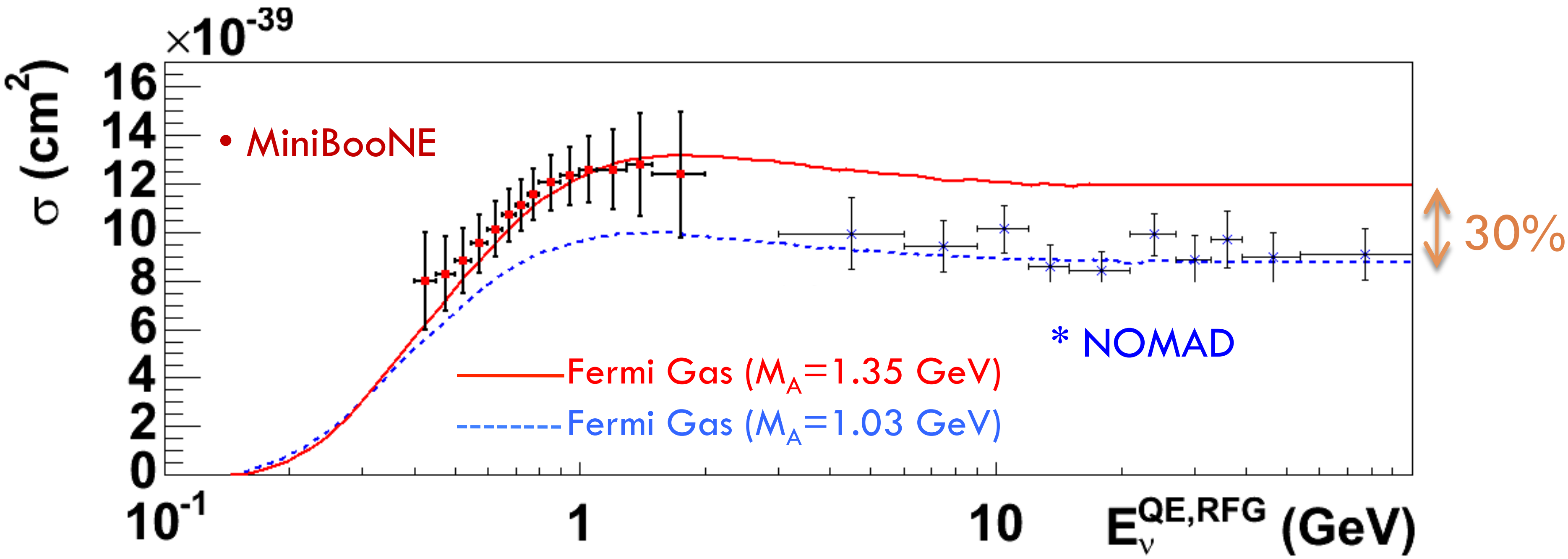


QE Cross Section on Carbon



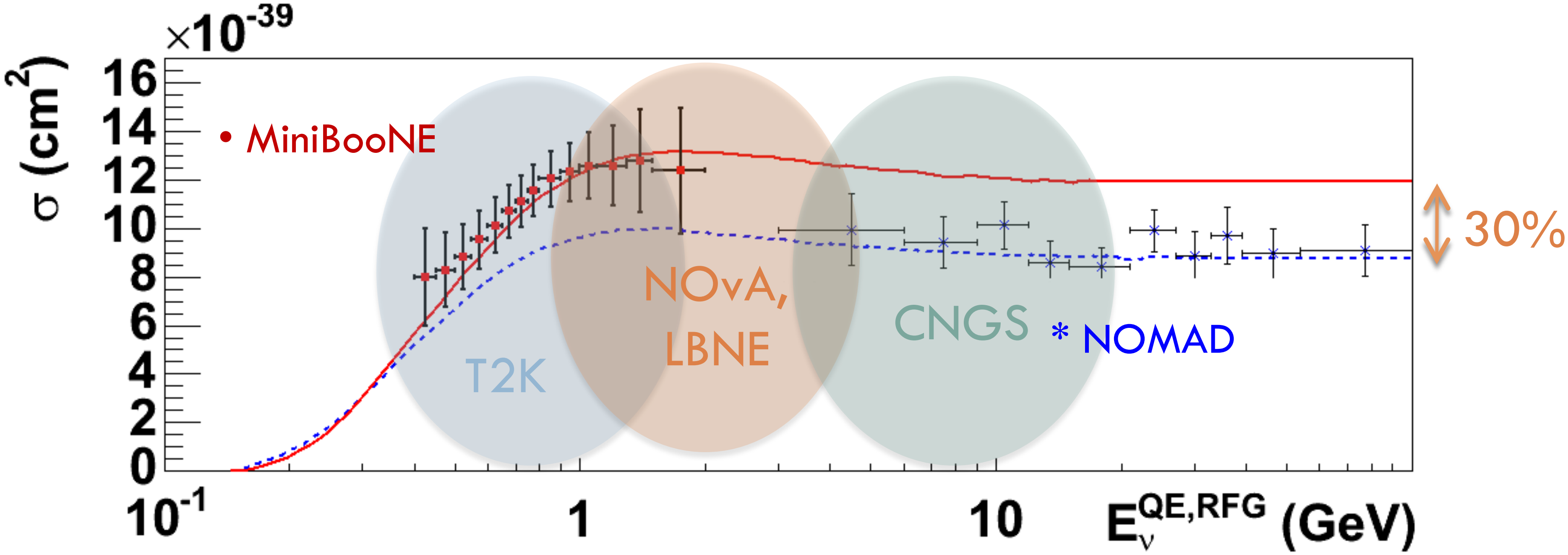
- MiniBooNE data is well above "standard" QE prediction
  (increasing M_A can reproduce σ)
- NOMAD data consistent with "standard" QE prediction
  (with M_A=1.0 GeV)

QE Cross Section on Carbon

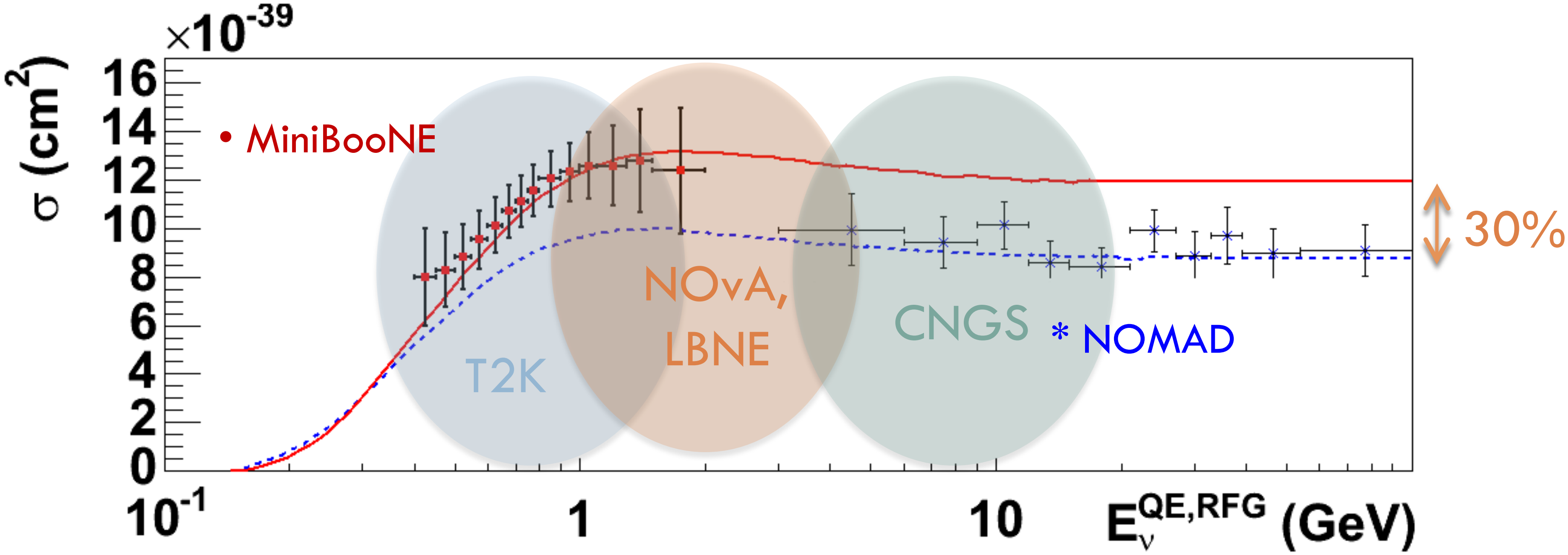


- results of low & high E experiments appear to be inconsistent; cannot be described with a single prediction
- difference is not many σ, but leaves you in a quandary if want to predict # signal events expect to see in your oscillation experiment

QE Cross Section on Carbon



QE Cross Section on Carbon



ArgoNeuT, MINERνA, MINOS

- good news is that new data will be weighing in on this soon that will exactly span this energy range

QE Cross Section at Low Energy

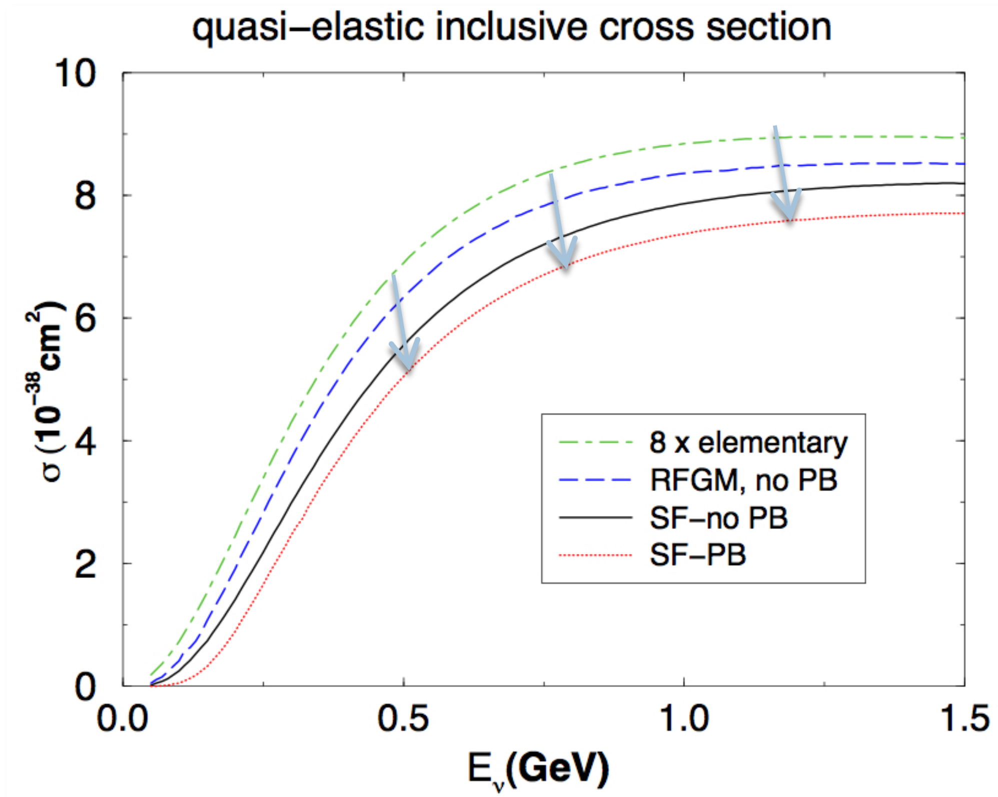
- MiniBooNE is the 1st time have measured the ν QE σ on a nuclear target at these low energies (< 2 GeV)

  - *naturally, these results have garnered a lot of attention, largely because they were unexpected*

    (increased QE rates also seen in K2K, SciBooNE, MINOS)

- naturally, attention focused on use of Fermi Gas model

- problem: adding nuclear effects decrease the σ



(O. Benhar, arXiv:0906.3144)

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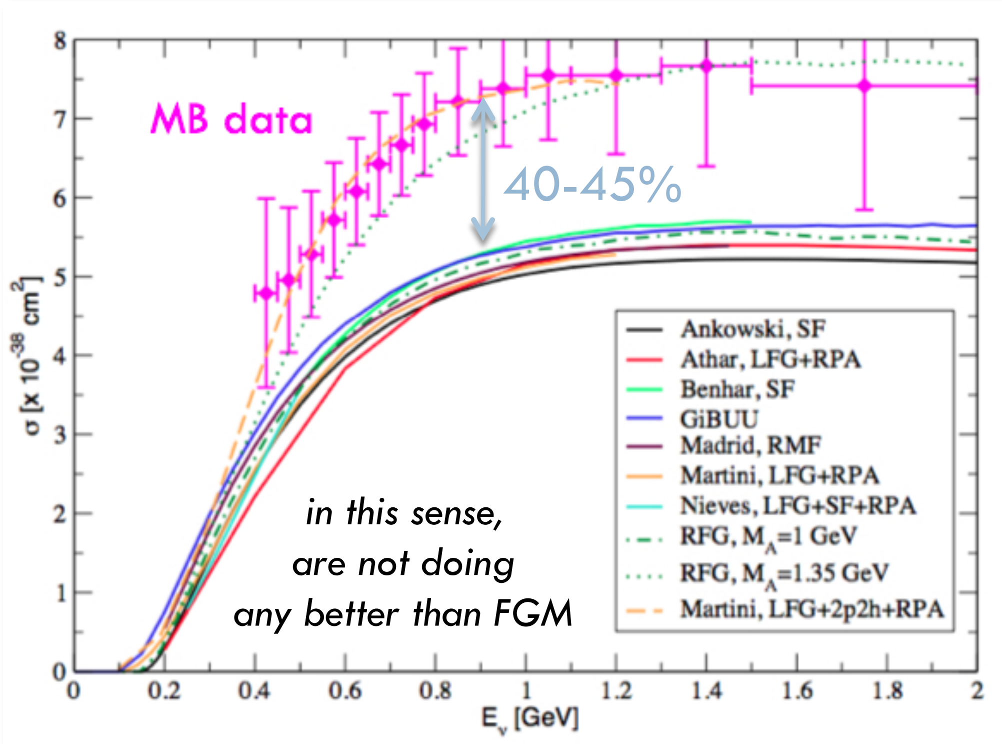
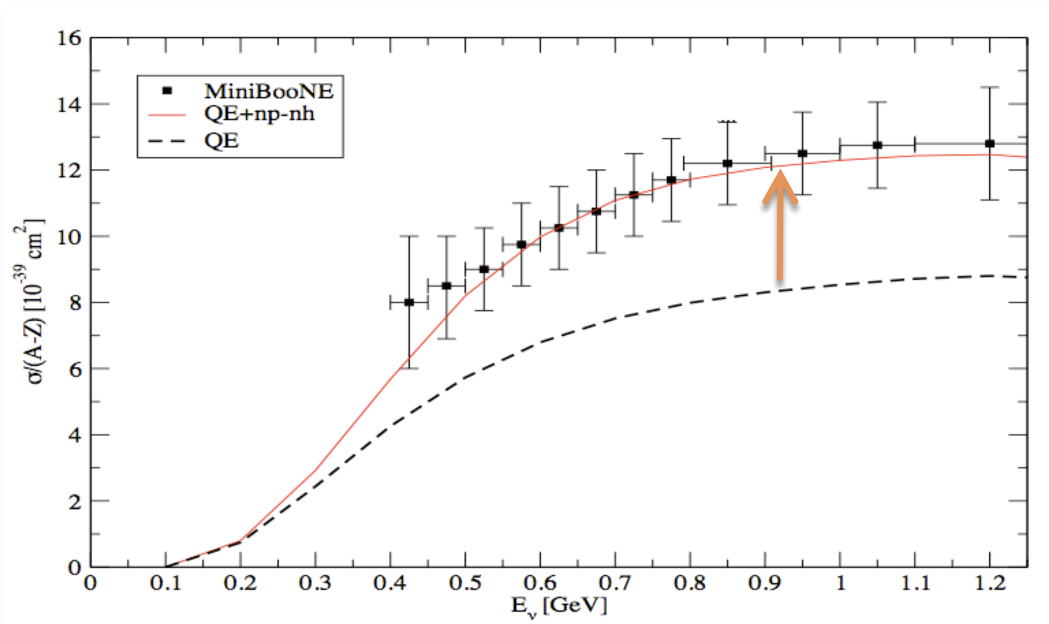


(L. Alvarez-Ruso, NuFact11)

- origin of this QE puzzle has been extensively debated

Nuclear Effects to the Rescue?

- a possible explanation has recently emerged …
- while traditional nuclear effects decrease the σ, there are processes that can increase the total yield



Martini *et al.*, PRC **80**, 065001 (2009)

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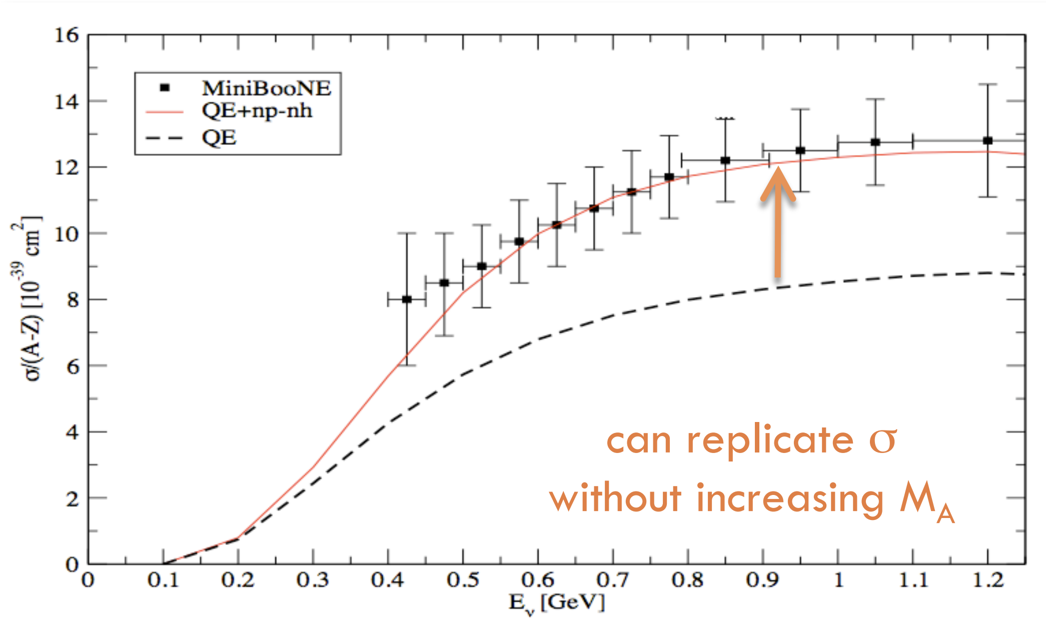

Martini *et al.*, PRC **80**, 065001 (2009)

- there are add'l nuclear dynamics present

  (i.e., effects not included in the independent particle approaches we have been using for decades)

- ν can scatter off of a strongly correlated nucleon state; <u>multi-nucleon correls</u> produce an enhancement

  (most important distinction is that E & $\vec{p}$ are absorbed by two or more nucleons, not a single nucleon)

Nuclear Effects to the Rescue?

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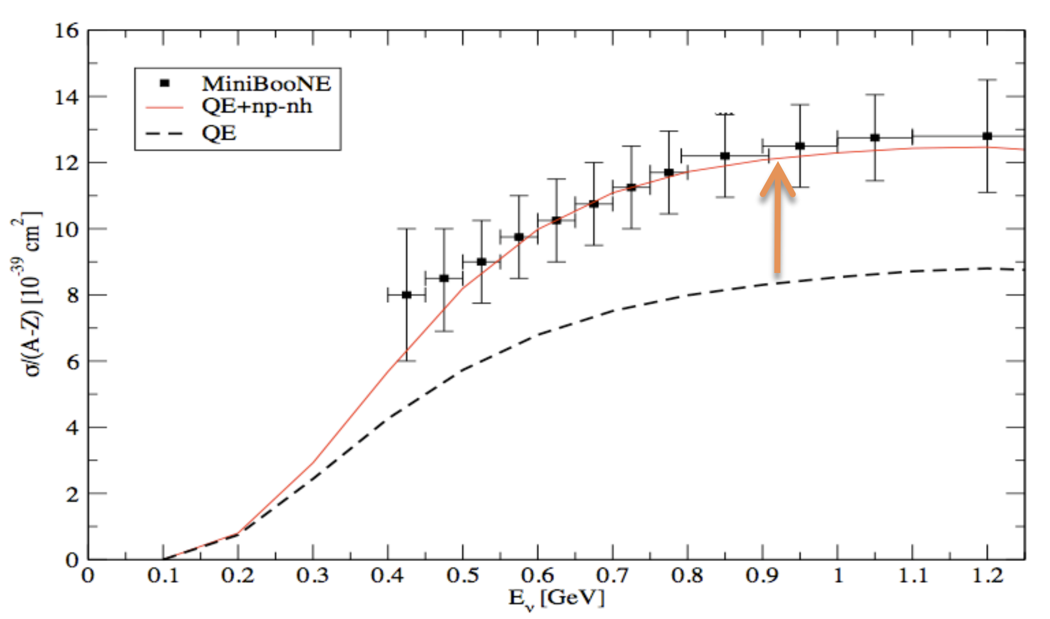
- while traditional nuclear effects decrease the σ, there are processes that can increase the total yield



Martini *et al.*, PRC **80**, 065001 (2009)

- idea is not new
  - Dekker *et al.*, PLB **266**, 249 (1991)
  - Singh, Oset, NP **A542**, 587 (1992)
  - Gil *et al.*, NP **A627**, 543 (1997)
  - J. Marteau, NPPS **112**, 203 (2002)
  - Nieves *et al.*, PRC **70**, 055503 (2004)

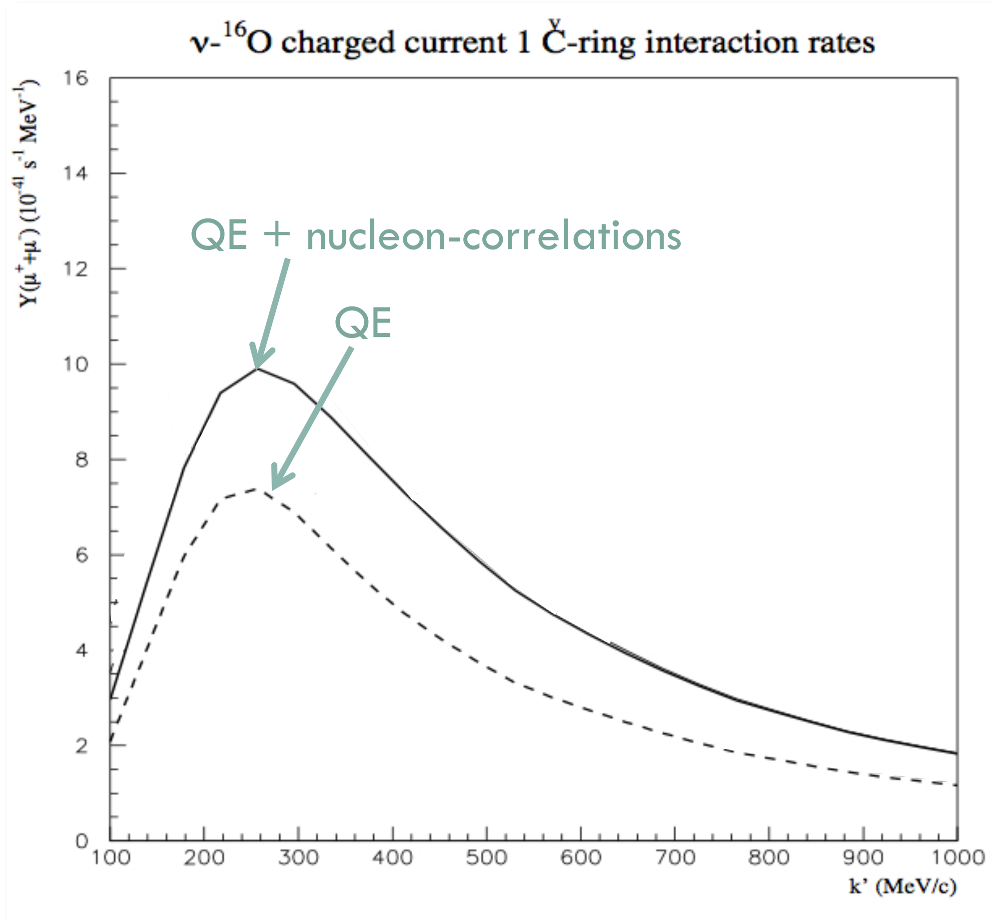
oldest models pre-date the experimental results

Not a New Idea

- in 1999, recognized that may not be able to distinguish these two contributions
- warned that could see 20% more 1-ring events in Super-K

"QE" = true QE + nucleon-correls
(μ+p) (μ+p+p)

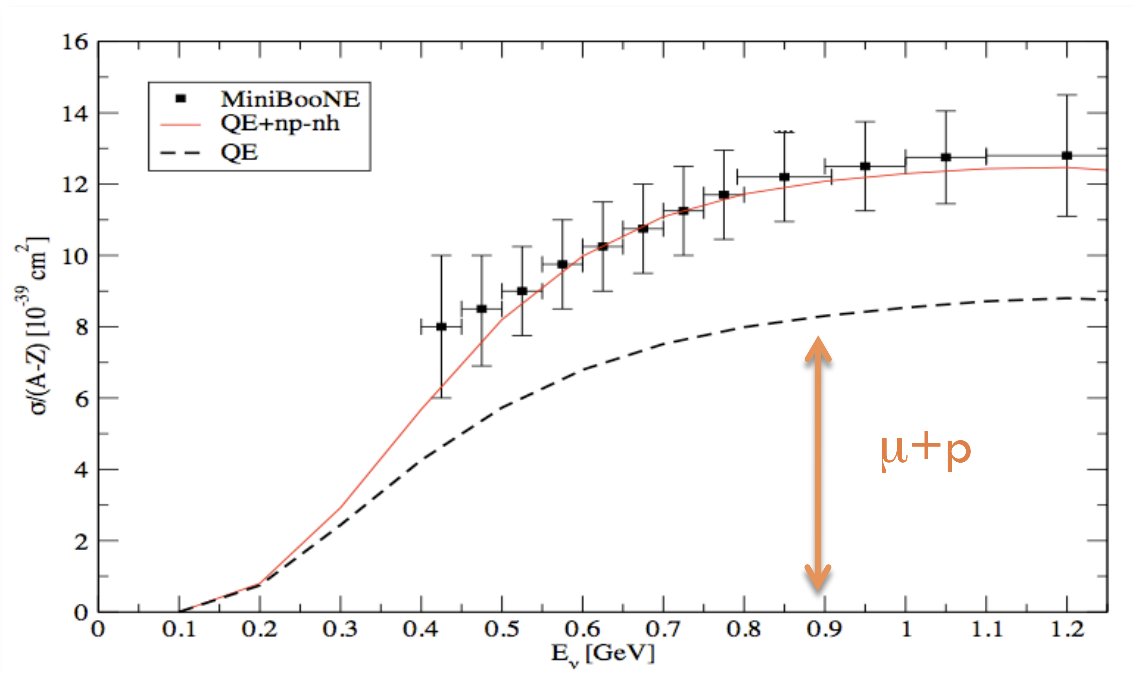
we see an enhacement of the total yield with respect to the free quasi-elastic around 20 %. This result points out the importance of a good evaluation of such neutrino induced *np-nh* excitations.



J. Marteau, Eur. Phys. J. **A5**, 183 (1999)

Nuclear Effects to the Rescue?

- idea is that there are <u>two contributions</u> present when we talk about ν QE scattering off of a nuclear target:



Martini *et al.*, PRC **80**, 065001 (2009)

← "standard" QE prediction we saw earlier (μ+p)

(single-nucleon knock-out; same as would get for free nucleon scattering)

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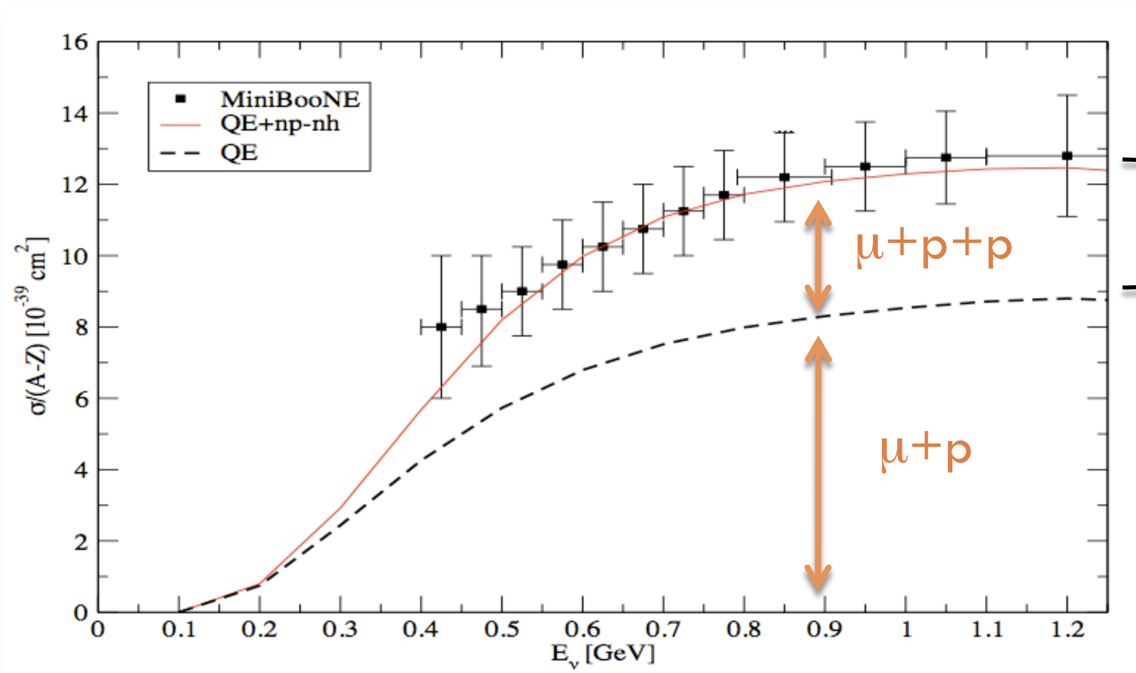

Martini *et al.*, PRC **80**, 065001 (2009)

scattering off of correlated nucleon states contributes up to 40% more σ at these ν energies and produces a multi-nucleon final state (μ+p+p)

(would not have seen this large effect in D_2 so this would have been missed)

Nuclear Effects to the Rescue?

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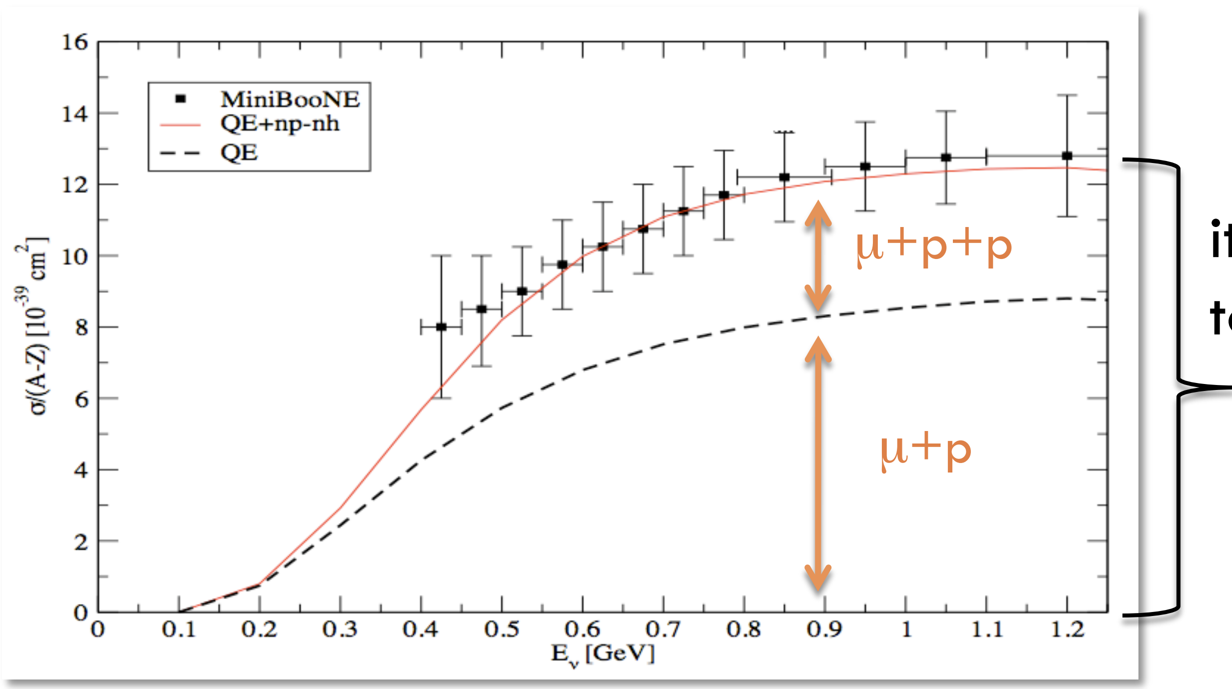

Martini *et al.*, PRC **80**, 065001 (2009)

it has been suggested that together account for MB

these two final states are indistinguishable in MB and in Cerenkov detectors in general

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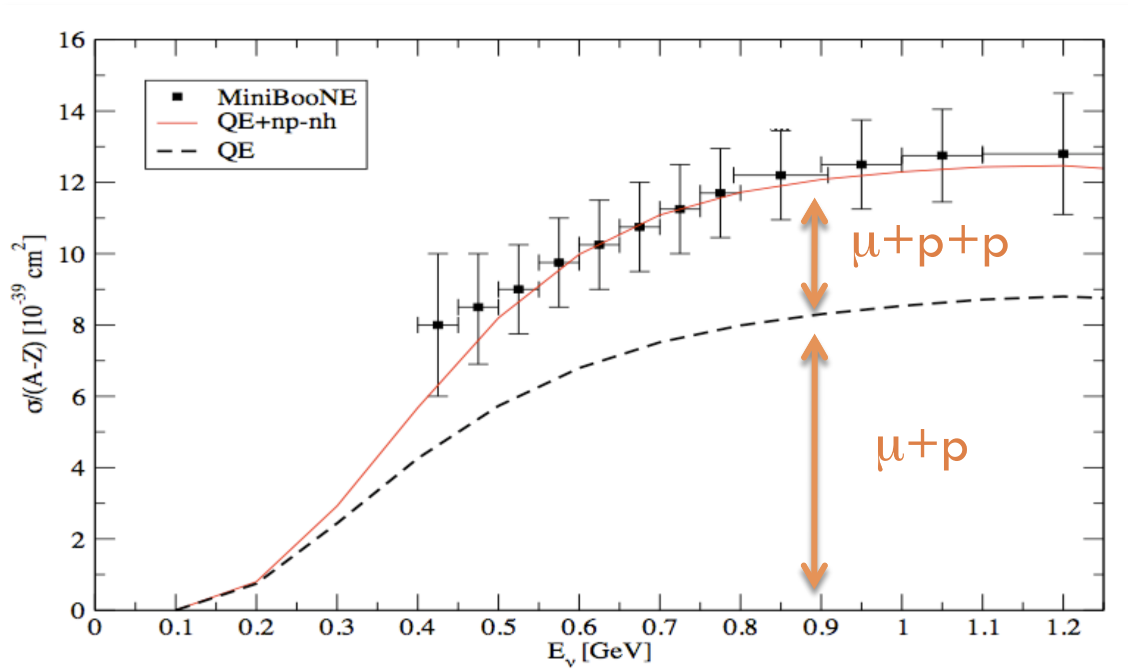


Martini *et al.*, PRC **80**, 065001 (2009)

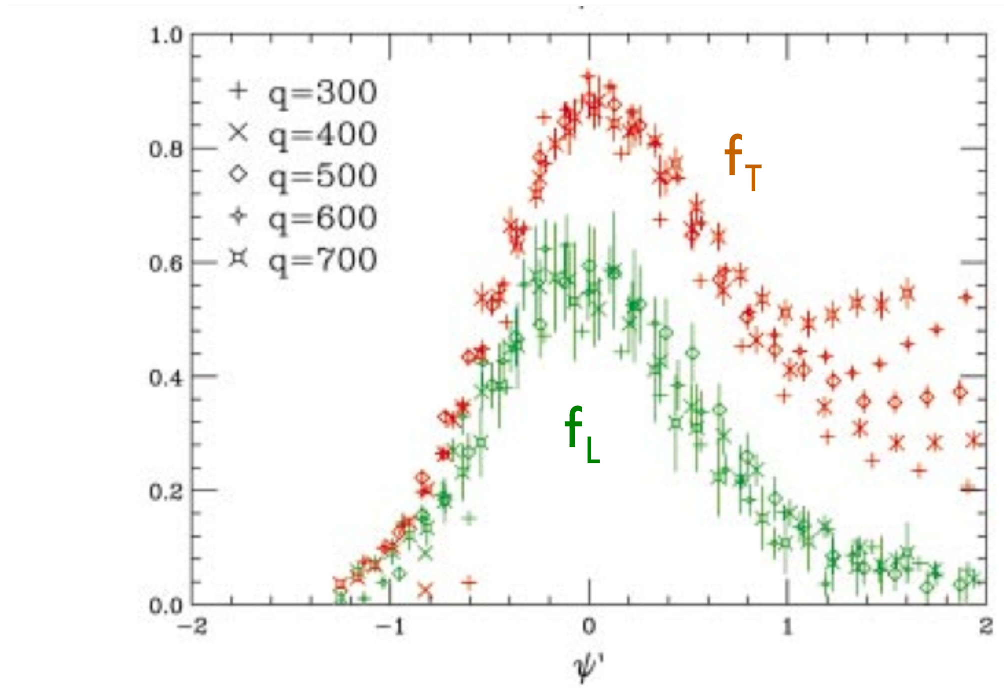
- could this explain the difference between MiniBooNE & NOMAD?

jury is still out on this

need to be clear what we mean by "QE" when scattering off nuclear targets!

Supporting Evidence from e⁻ QE Scattering

- while this is new to ν scattering, has been known for over 2 decades in e⁻ case (G. Garvey)



← can separate out L, T

Carlson *et al.*, PRC **65**, 024002 (2002)

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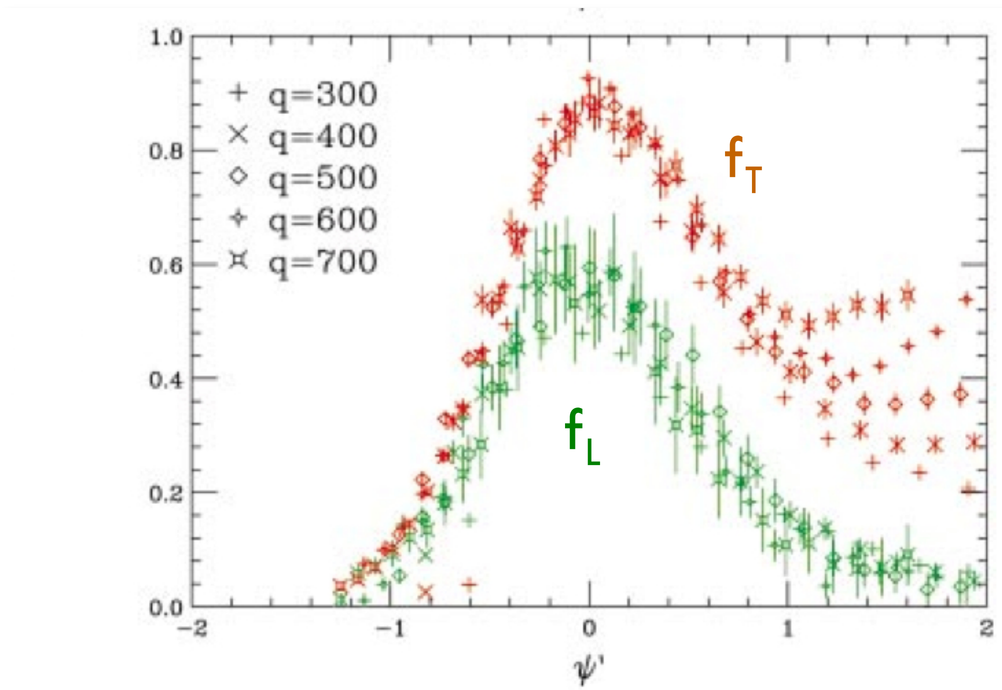

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- **longitudinal** part of σ_{QE} can be described in terms of scattering off independent nucleons

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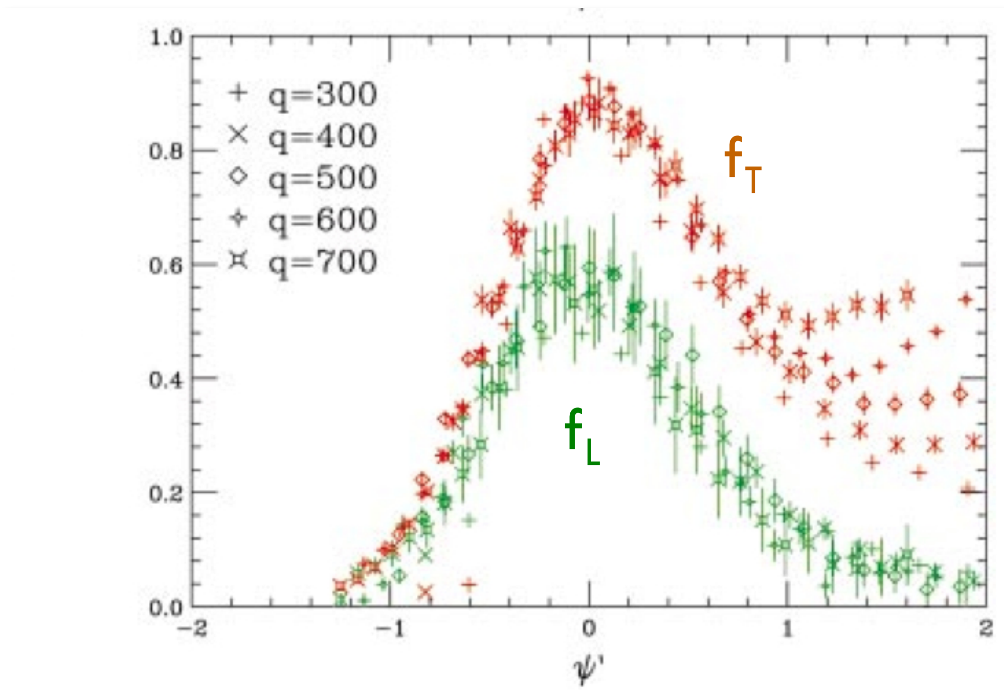

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  (can be explained by SRC and 2-body currents)

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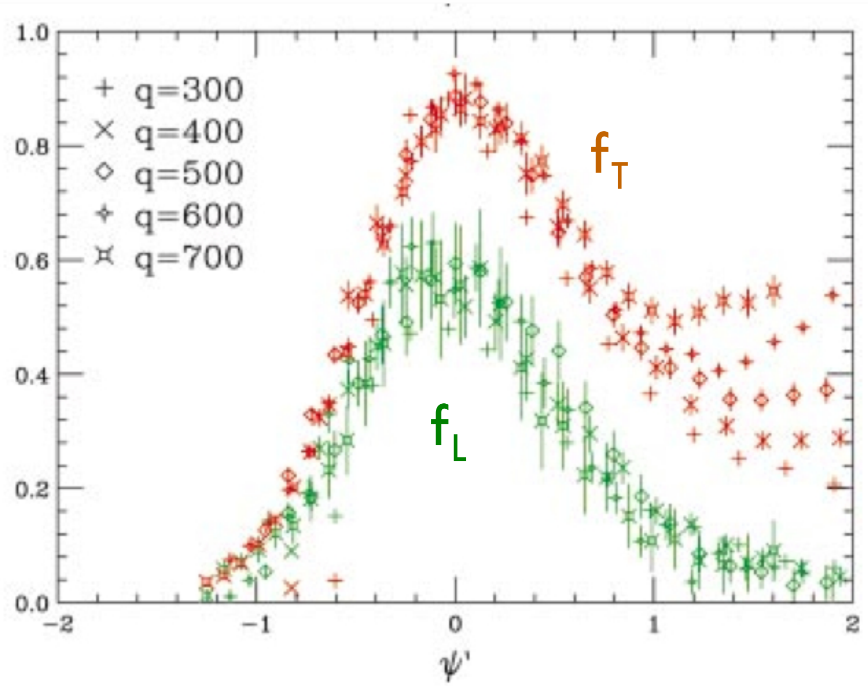

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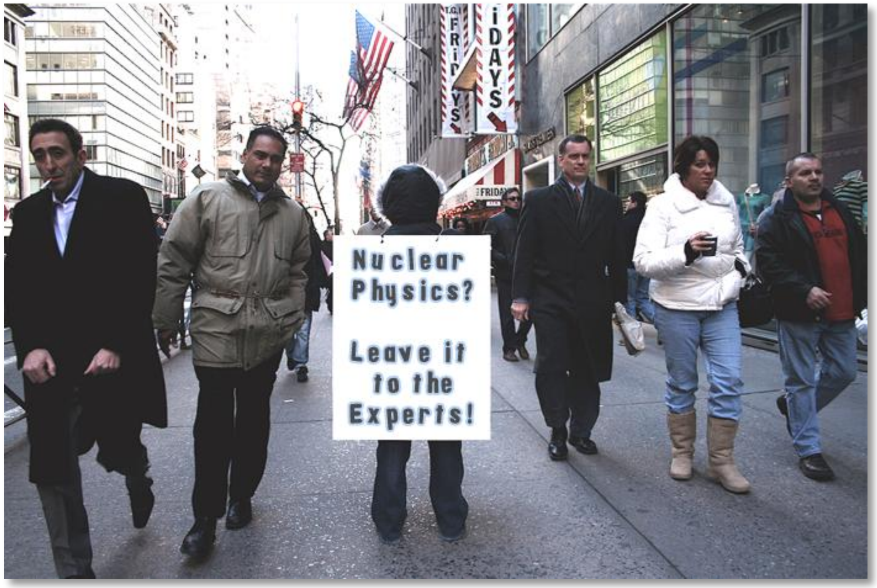
- **longitudinal** part of σ_{QE} can be described in terms of scattering off independent nucleons
- in contrast, see a very large enhancement in **transverse** part
  (can be explained by SRC and 2-body currents)
- implies that there should also be a corresponding transverse enhancement in ν QE scattering!

- took us awhile to realize that we may be seeing the same thing in ν scattering … now widespread acceptance …

Has Been a Focus in the Past Year

- over 50 theoretical papers on the topic of QE ν-nucleus scattering

  - Lalakulich *et al.*, arXiv:1203.2935
  - Mosel, arXiv:1204.2269, 1111.1732
  - Barbaro *et al.*, arXiv:1110.4739
  - Giusti *et al.*, arXiv:1110.4005
  - Meloni, arXiv:1203.3335, 1110.1004
  - Martini *et al.*, arXiv:1202.4745, 1110.0221, 1110.5895, Phys. Rev **C81**, 045502 (2010)
  - Paz, arXiv:1109.5708
  - Sobczyk, arXiv:1201.3673, 1109.1081, 1201.3673
  - Nieves *et al.*, arXiv:1106.5374, 1110.1200, Phys. Rev. **C83**, 045501 (2011)
  - Bodek *et al.*, arXiv:1106.0340
  - Amaro, *et al.*, arXiv:1104.5446, 1112.2123, 1012.4265, Phys. Lett **B696**, 151 (2011)
  - Antonov, *et al.*, arXiv:1104.0125
  - Benhar, *et al.*, arXiv:1012.2032, 1103.0987, 1110.1835
  - Meucci *et al.*, arXiv:1202.4312, Phys. Rev. **C83**, 064614 (2011)
  - Ankowski *et al.*, Phys. Rev. **C83**, 054616 (2011)
  - Alvarez-Ruso, arXiv:1012.3871
  - Martinez *et al.*, Phys. Lett **B697**, 477 (2011)



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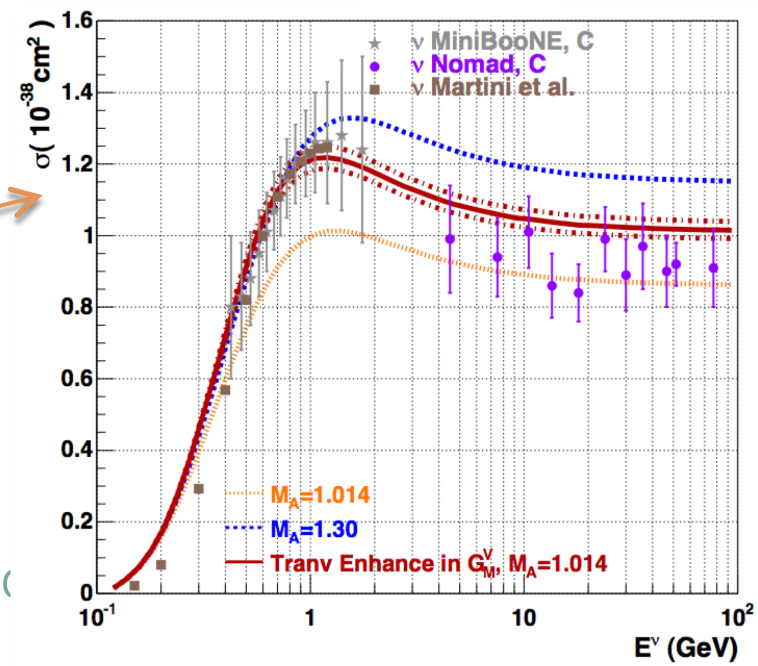
  - Ankowski *et al.*, Phys. Rev. **C83**, 054616 (2011)
  - Alvarez-Ruso, arXiv:1012.3871
  - Martinez *et al.*, Phys. Lett **B697**, 477 (2011)

(most of calcs have been focused on low E, but there has been new work to incorporate increased transverse response from e⁻)



- however, need to do more

Moving Forward

- also new approaches on the experimental side …

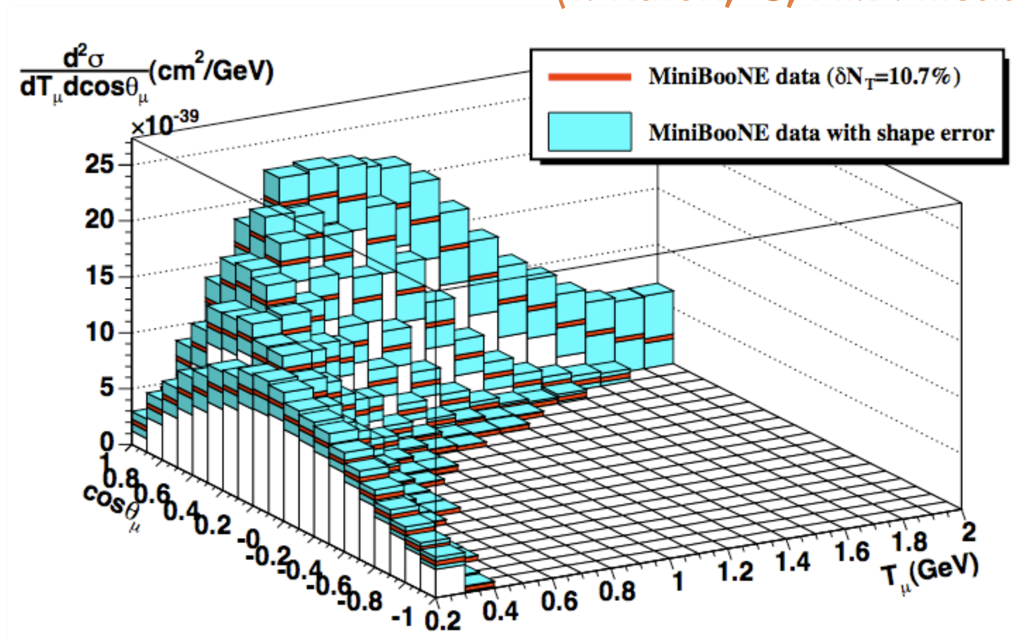
(T. Katori, IU, Ph.D. thesis)

- double differential σ's for the first time!

  $d^2\sigma/dT_\mu d\theta_\mu$

- 146,000 ν_μ "QE" events
  (currently world's largest sample)

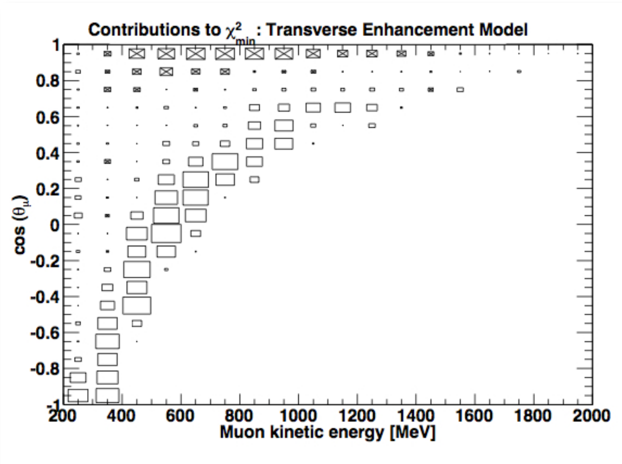
- historically, never had enough statistics to do this



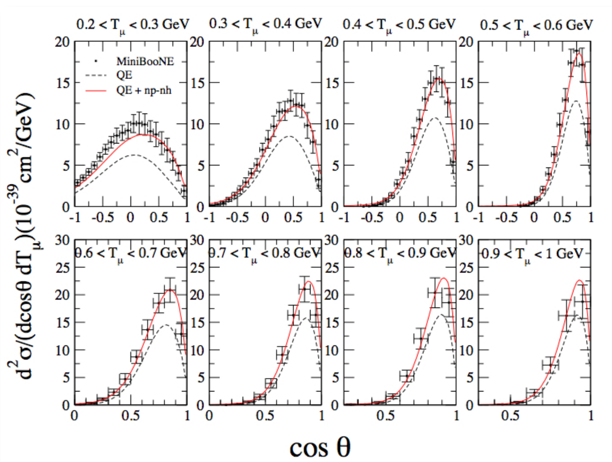
Aguilar-Arevalo *et al.*, PRD **81**, 092005 (2010)

- most model-independent result possible, provides richer info than $\sigma(E_\nu)$
  - *this data is getting heavily used by the community*

Double Differential σ Comparisons

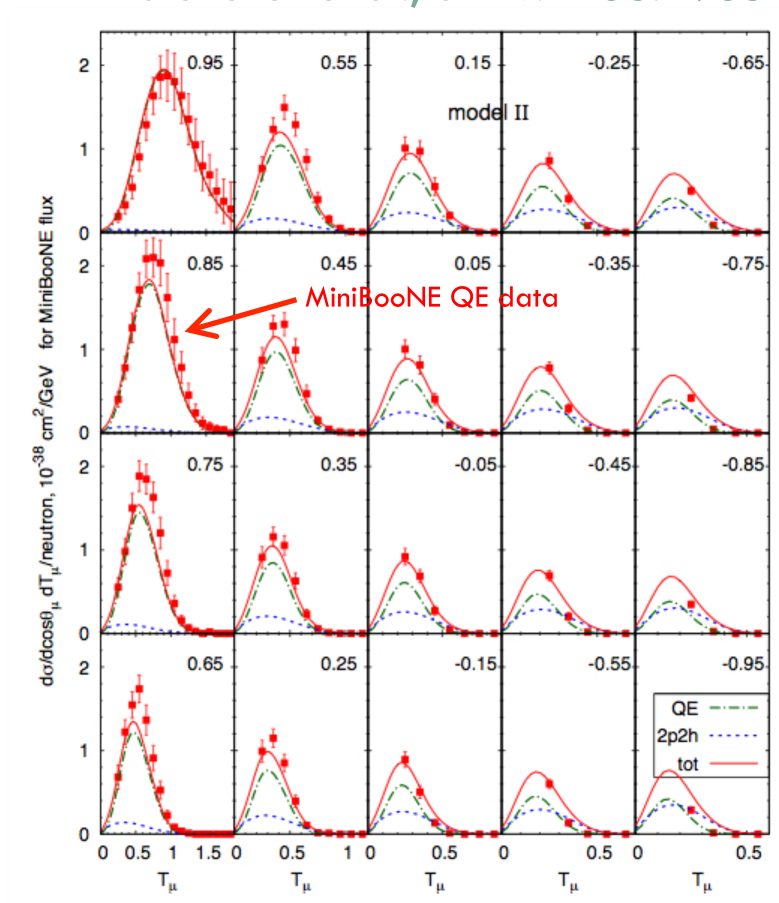


Sobczyk, arXiv:1109.1081



Martini *et al.*, arXiv:1110.0221

Lalakulich *et al.*, arXiv:1203.2935



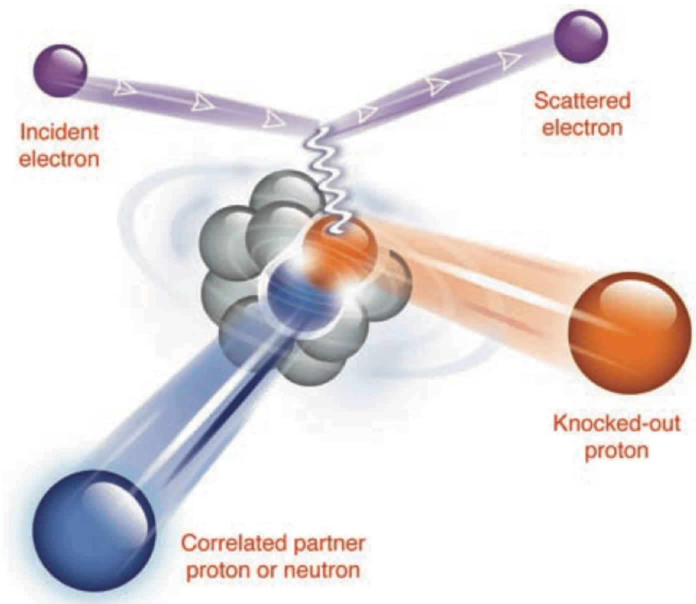
1[st] time we've had this sort of info available

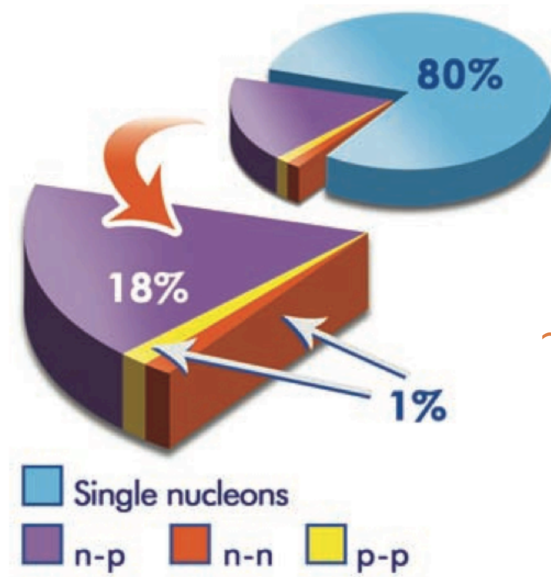
- would be nice to have measurements at other E_ν, A and of the outgoing proton(s)!

Smoking Gun …

- e⁻ scattering experiments have already provided evidence for SRC

  *big splash in Science magazine: R. Subedi et al., Science **320**, 1476 (2008)*





determined that ~20% of nucleons in carbon are in a correlated state

- direct measurement of multi-nucleon final states in a ν detector could play an important role in verifying scattering from such correlated nucleon states (early attempts by NOMAD, Veltri *et al.*, NP **B609**, 255 (2001))

Could We See This?

- if nucleon correlations are significant, this should produce a distinguishable final state … this has be observable!

(so not only the enhanced σ, but also multiple recoil nucleons)

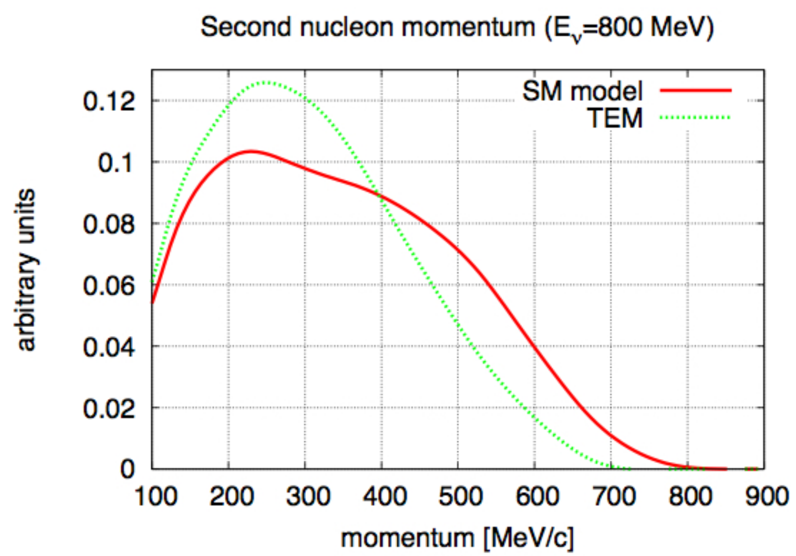
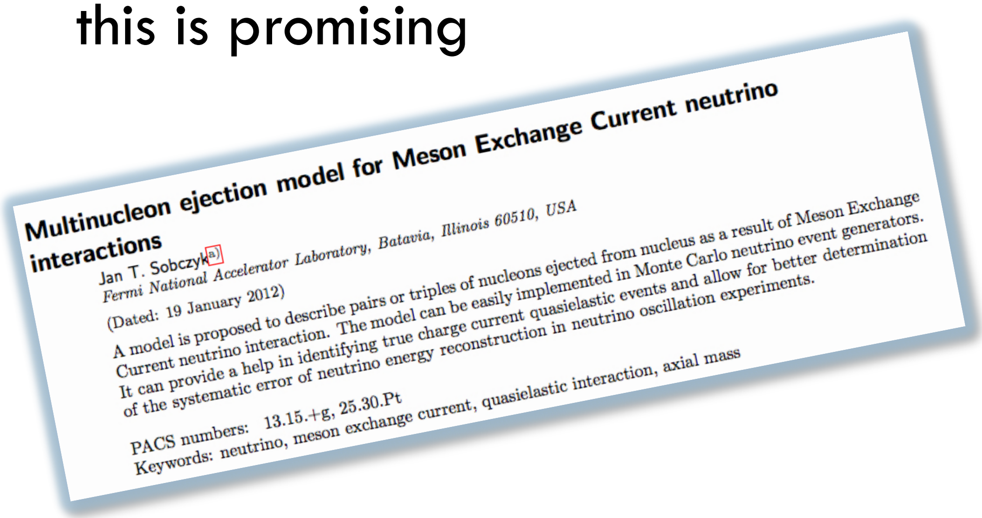


FIG. 11. Momentum of the second most energetic nucleon in the final state. Neutrino energy is 800 MeV.

J. Sobczyk, arXiv:1201.3673 [hep-ph]

- people are just starting to work out these details for ν scattering

- recent paper suggests that this is promising



Multinucleon ejection model for Meson Exchange Current neutrino interactions

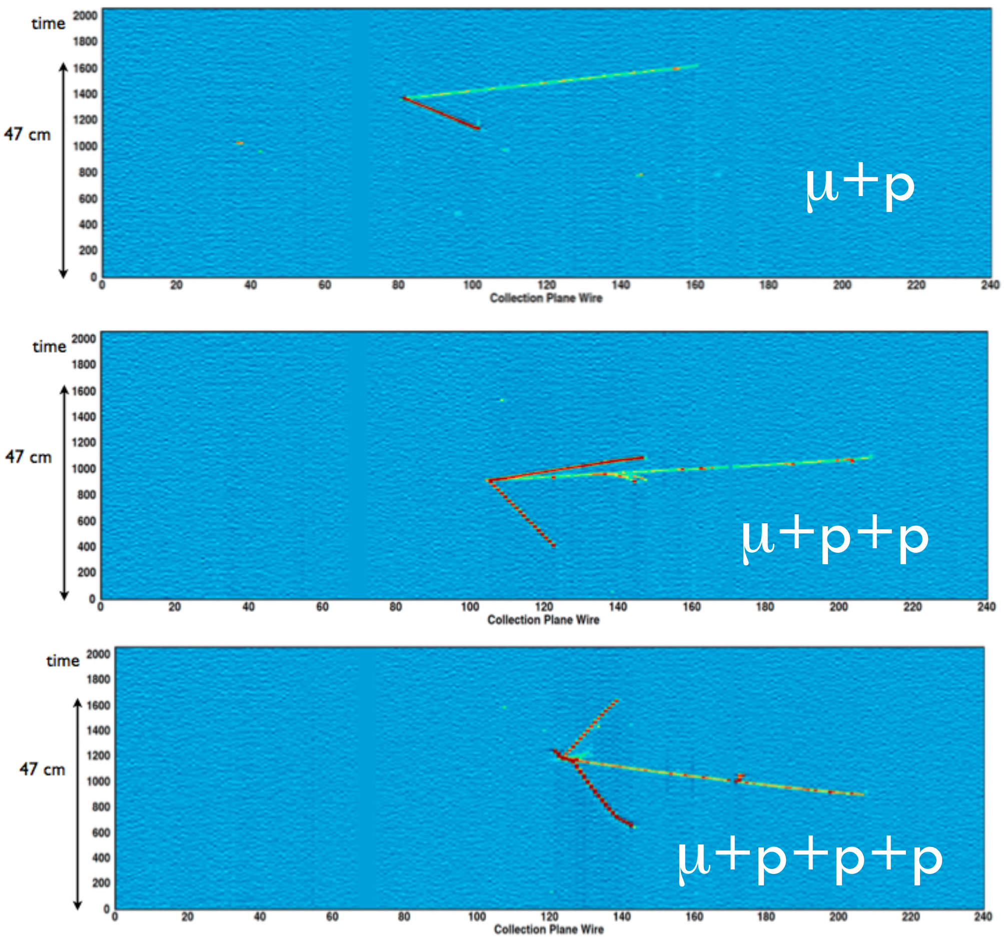
Jan T. Sobczyk[a)]
Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA

(Dated: 19 January 2012)

A model is proposed to describe pairs or triples of nucleons ejected from nucleus as a result of Meson Exchange Current neutrino interaction. The model can be easily implemented in Monte Carlo neutrino event generators. It can provide a help in identifying true charge current quasielastic events and allow for better determination of the systematic error of neutrino energy reconstruction in neutrino oscillation experiments.

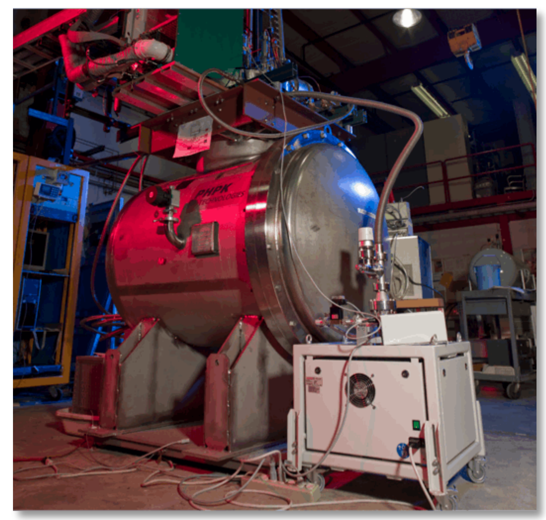
PACS numbers: 13.15.+g, 25.30.Pt
Keywords: neutrino, meson exchange current, quasielastic interaction, axial mass

Promise of Liquid Argon TPCs



J. Spitz, arXiv:1009.2515 [hep-ex]

- perhaps one of our best chances to see this will be in a LAr TPC
  (can detect protons down to very low energy)



- **ArgoNeuT** = 175L LAr TPC
  ran in the NuMI beam (2009-2010);
  there is also ICARUS and MicroBooNE!

- but need to disentangle from FSI!

What Does This All Mean?

- something as simple as QE scattering is not so simple
  - nuclear effects can significantly <u>increase</u> the cross section
  - idea that could be missing ~40% of σ in our simulations is a big deal!

- <u>good news</u>: expect larger event yields

- <u>bad news</u>: need to understand the underlying physics

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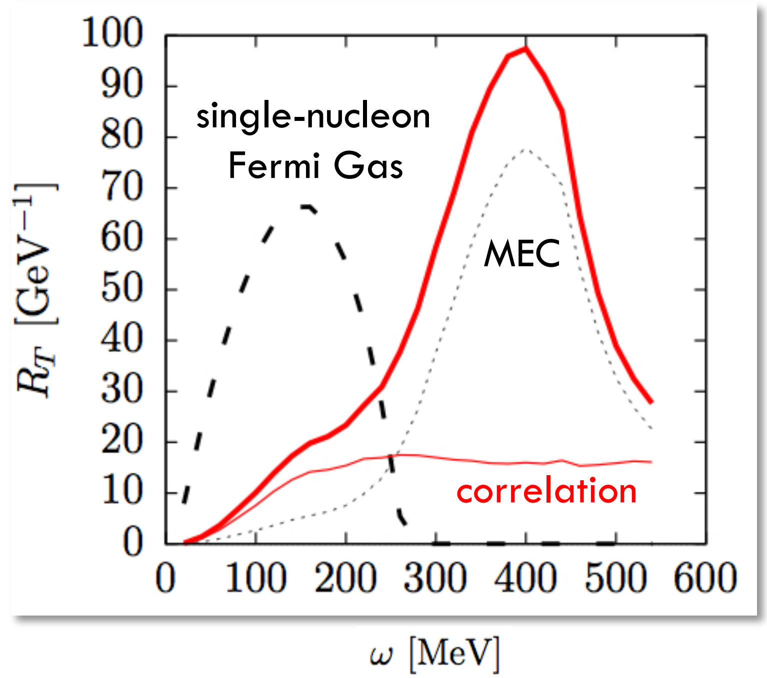
- <u>good news</u>: expect larger event yields
- <u>bad news</u>: need to understand the underlying physics

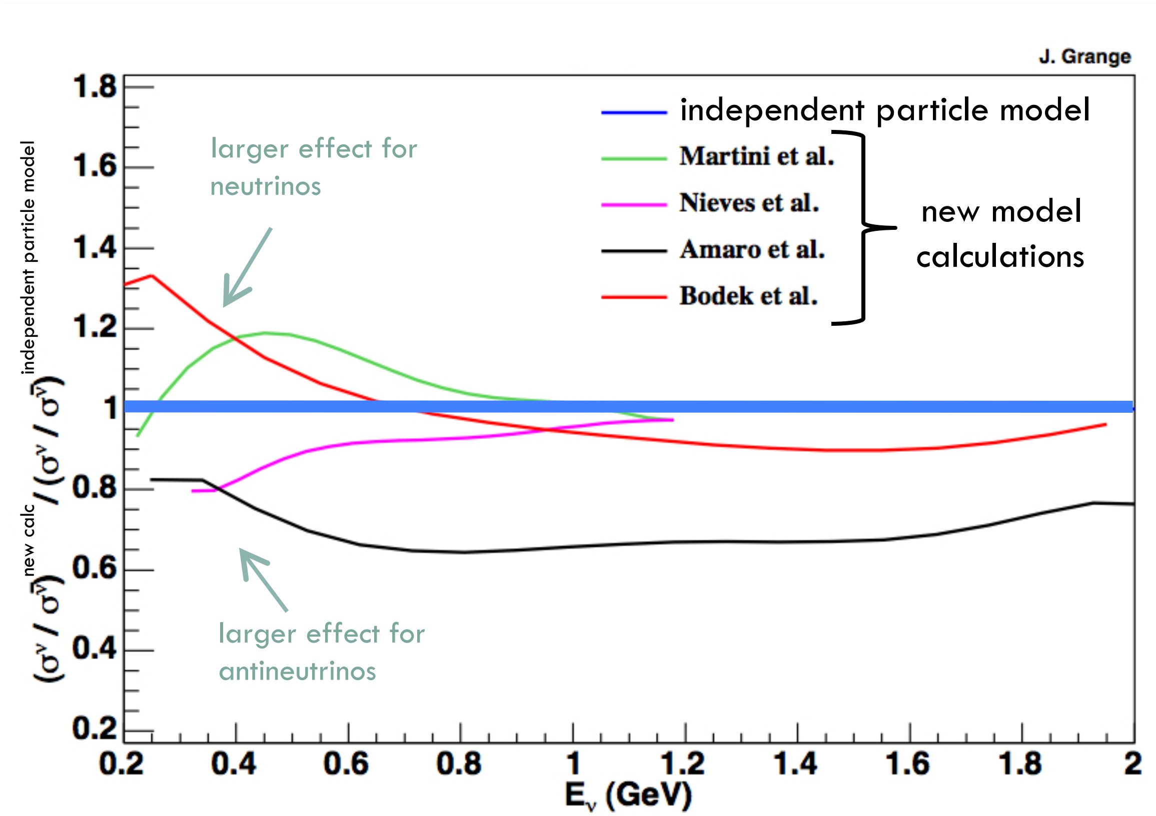
(1) impacts E_ν determination
Martini, arXiv:1202.4745; Meloni, arXiv:1203.3335
Lalakulich, arXiv:1203.2935

(2) effects will be different for ν vs. $\bar{\nu}$
(at worse, could produce a spurious $\cancel{CP}$ effect)



Amaro *et al.*, PRC **82**, 044601 (2010)

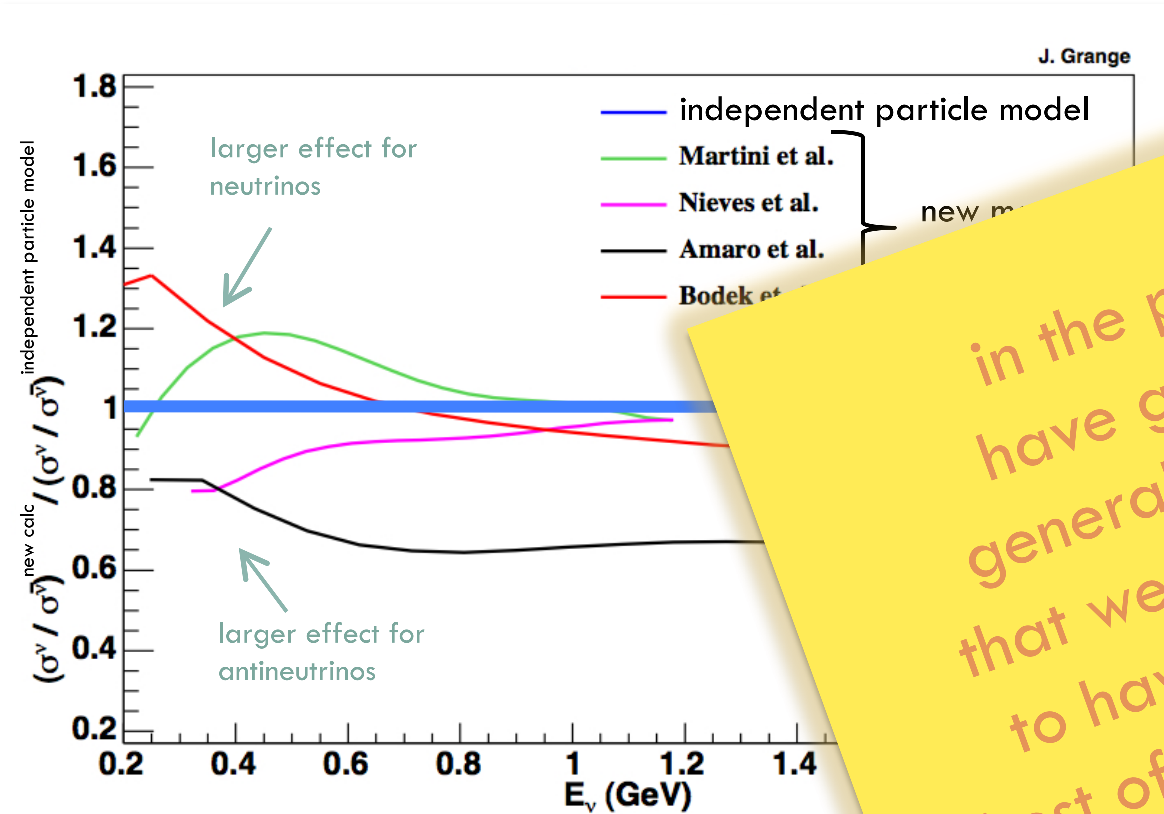
Neutrino/Antineutrino Ratio



we are currently working on a $\nu/\bar{\nu}$ σ_{QE} ratio measurement in MB that should have some discriminating power (J. Grange)

- theory calculations currently disagree over the size of these effects for antineutrinos
- the situation is unclear and will need to get resolved
- for large θ_{13}, the $\nu/\bar{\nu}$ asymmetry is small so will need a detailed understanding of these $\nu,\bar{\nu}$ differences!

Neutrino/Antineutrino Ratio



- theory ... ons ... ee ... ese ... rinos ... r ... ailed ... anding of these $\nu,\bar{\nu}$ differences!

in the past year, have gone from a general complacency that we know the QE σ_{ν} to having uncovered a host of rich nuclear effects

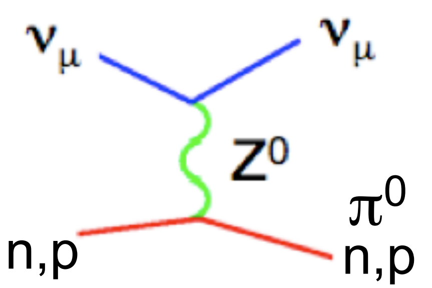
… story will continue to evolve

we are currently working on a $\nu/\bar{\nu}$ ratio measurement in MB that should h… some discriminating power (J. Grange)

Pion Production

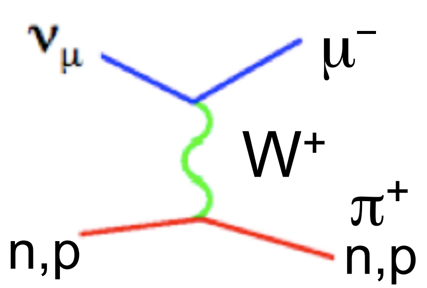
- NC π^0 production

(background for ν_e appearance)

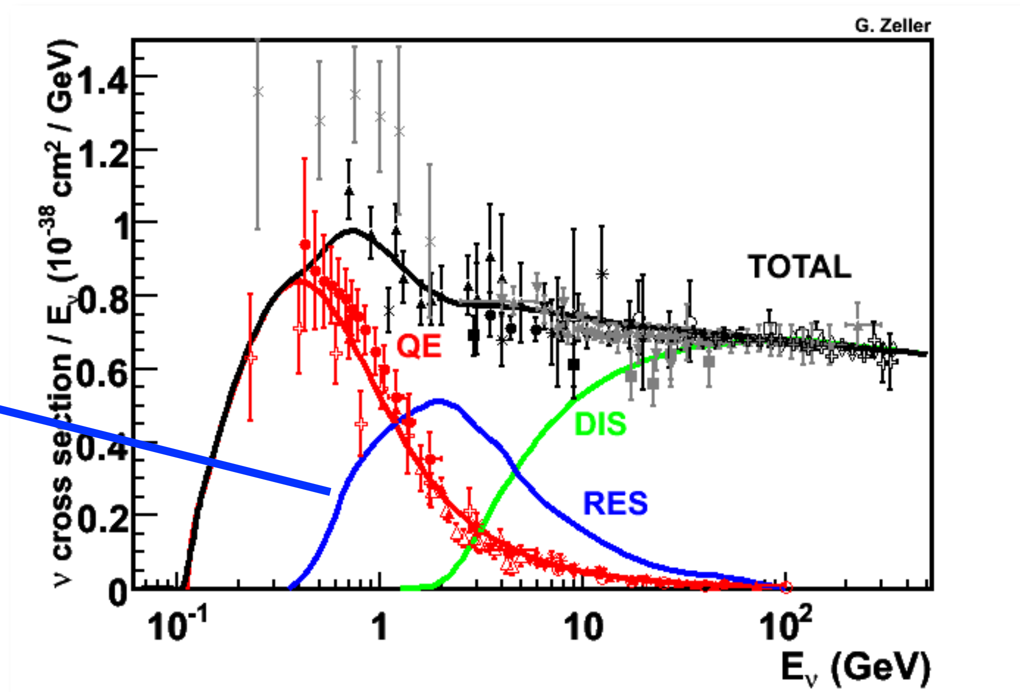


- CC π^+, π^0 production

(a complication for ν_μ disappearance)



- talked about QE (signal), what about bkgs?



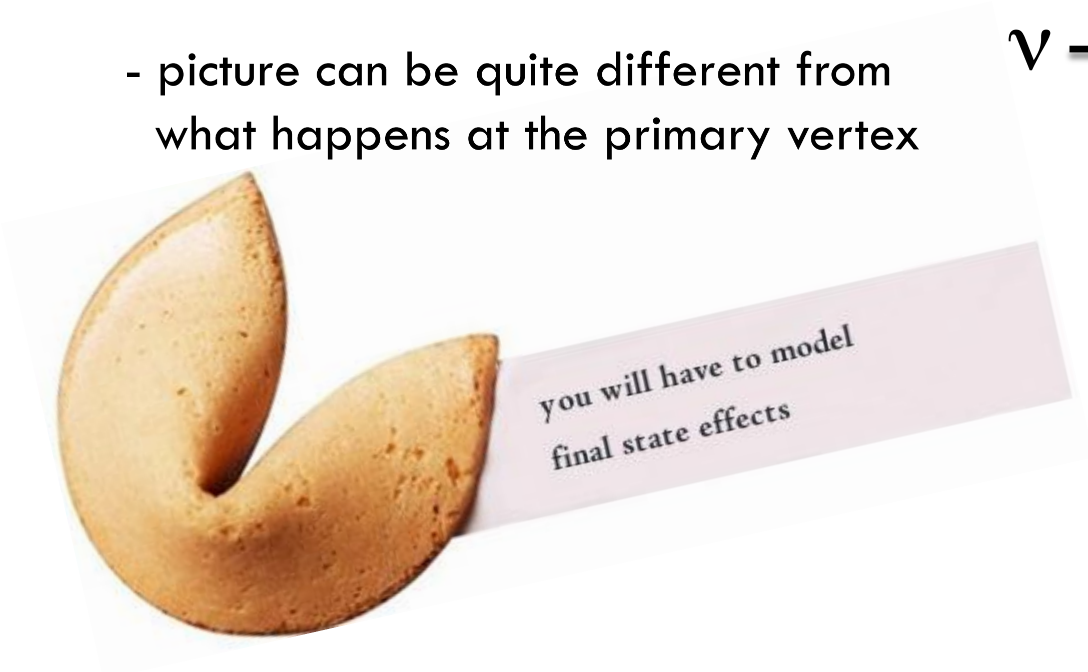
- π production also has important connections to ν osc measurements

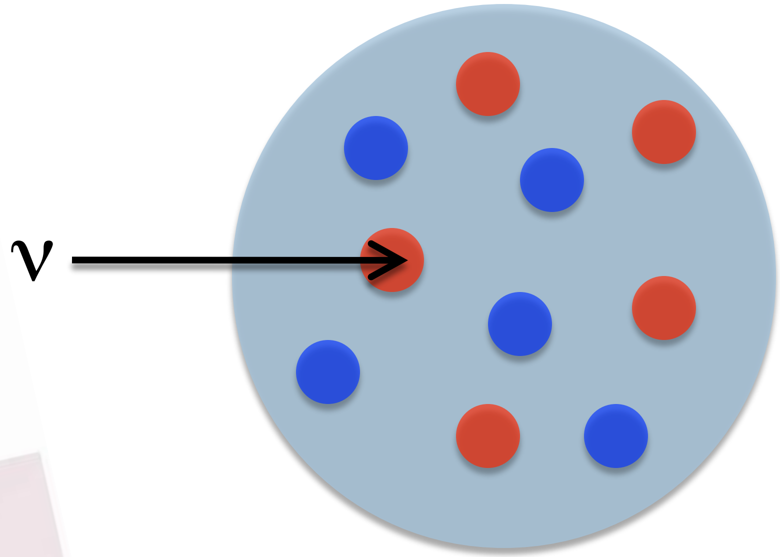
Final State Effects Can Change the Picture

- a new appreciation for nuclear effects in this region as well

"final state interactions (FSI)"

- before they leave the nucleus, pions & nucleons can re-interact
- picture can be quite different from what happens at the primary vertex





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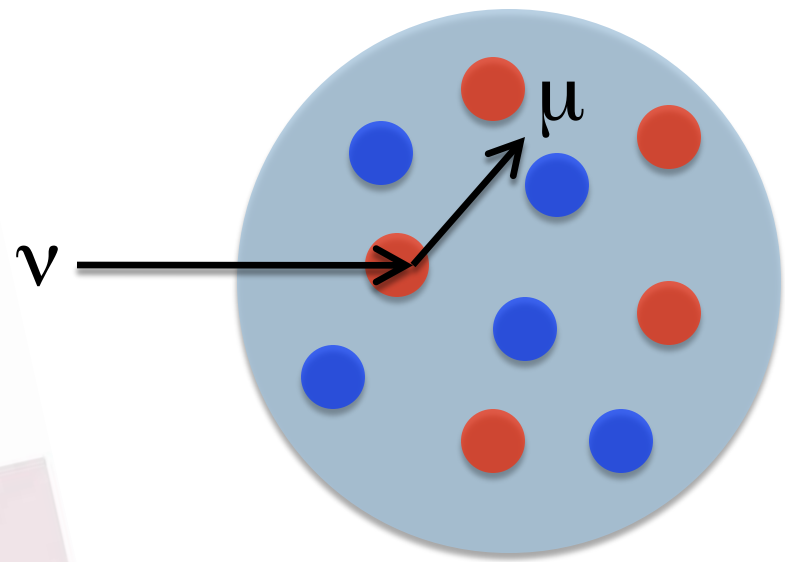

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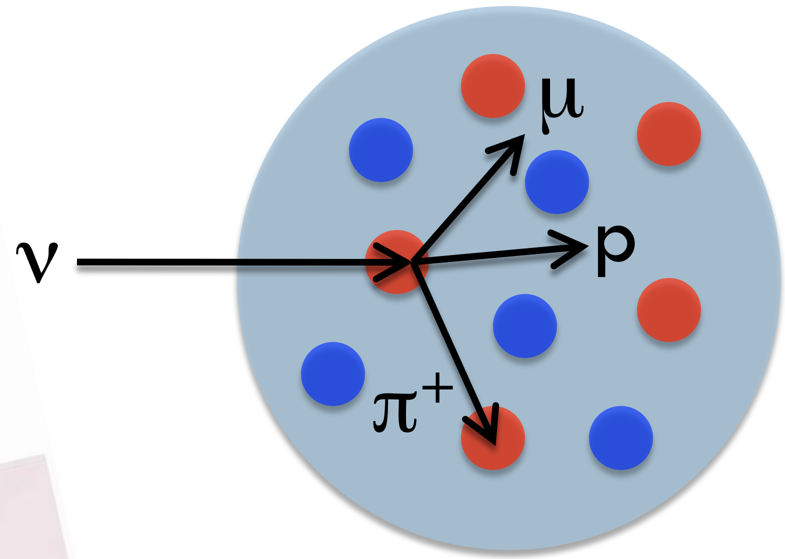

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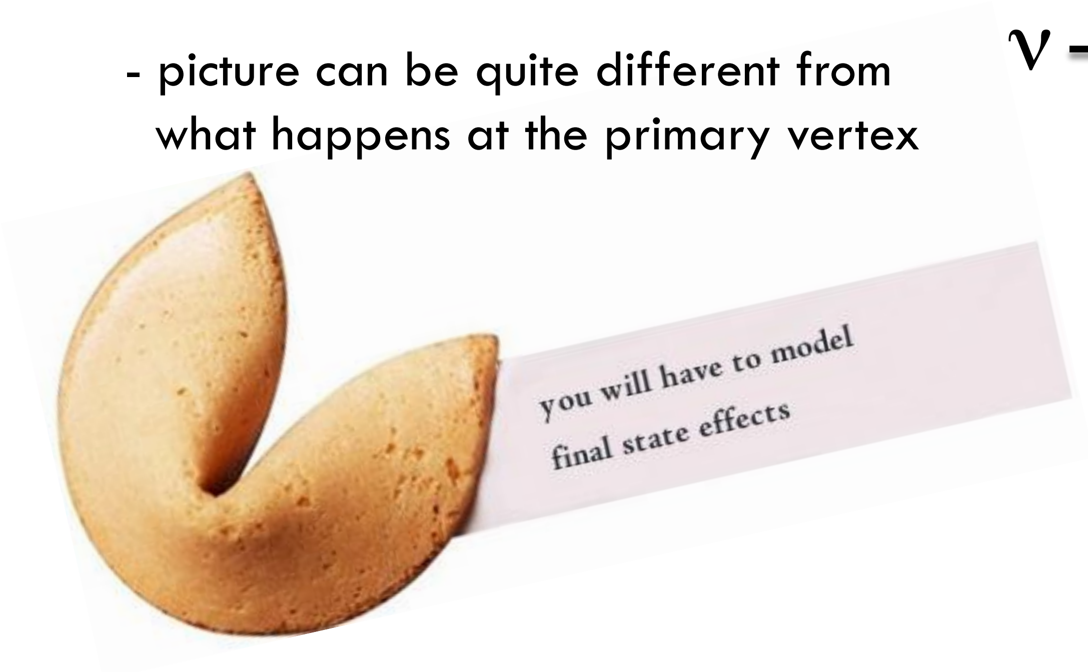

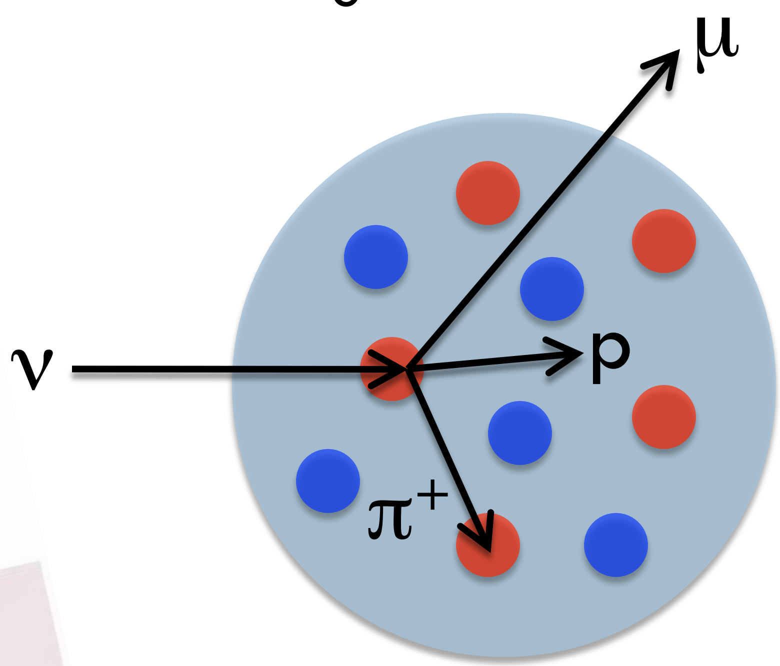

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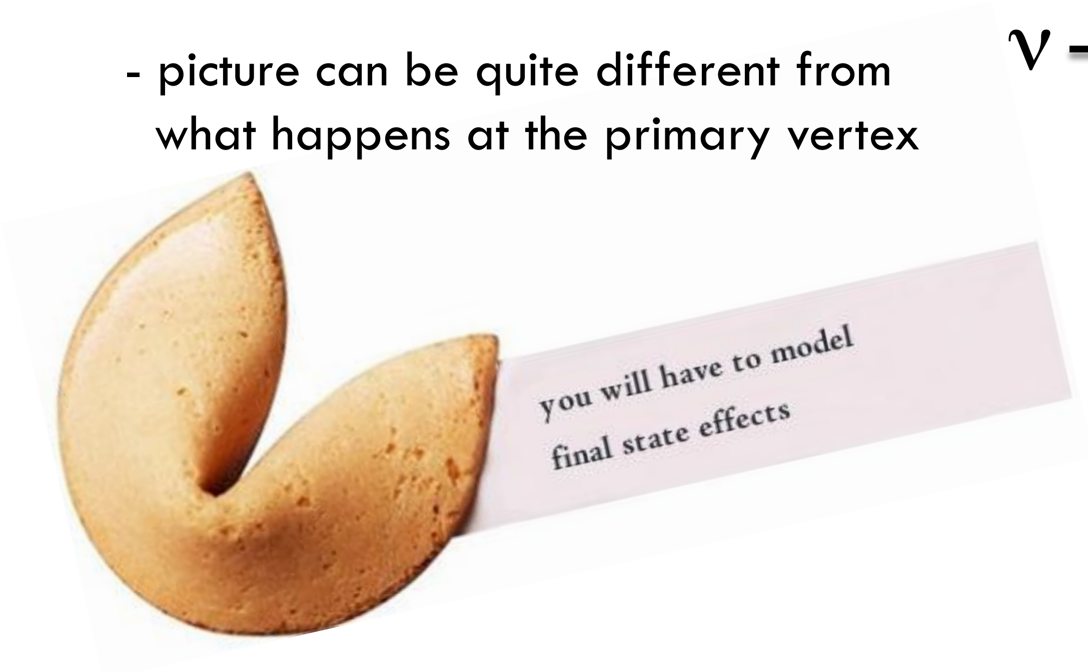

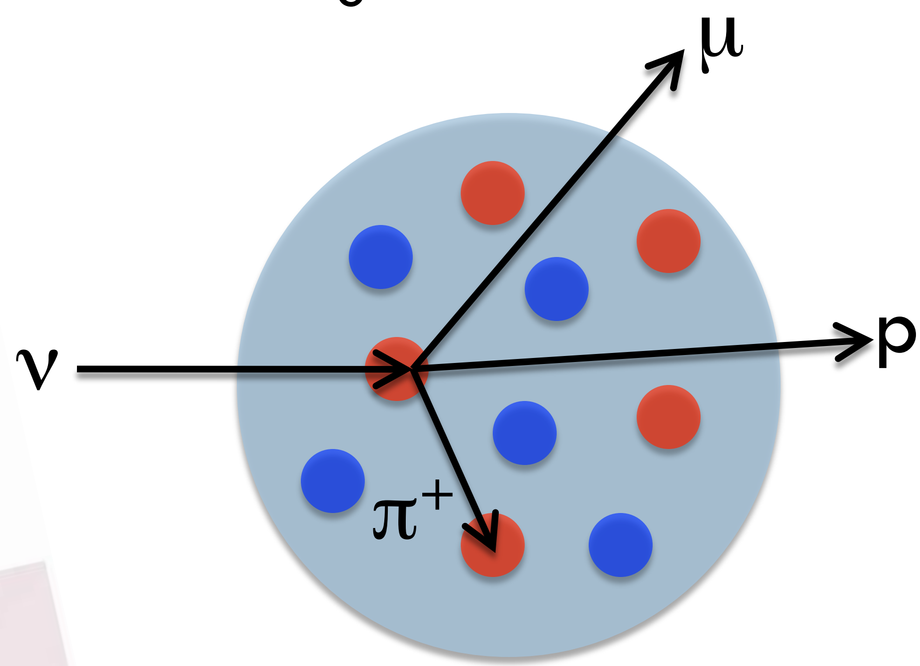

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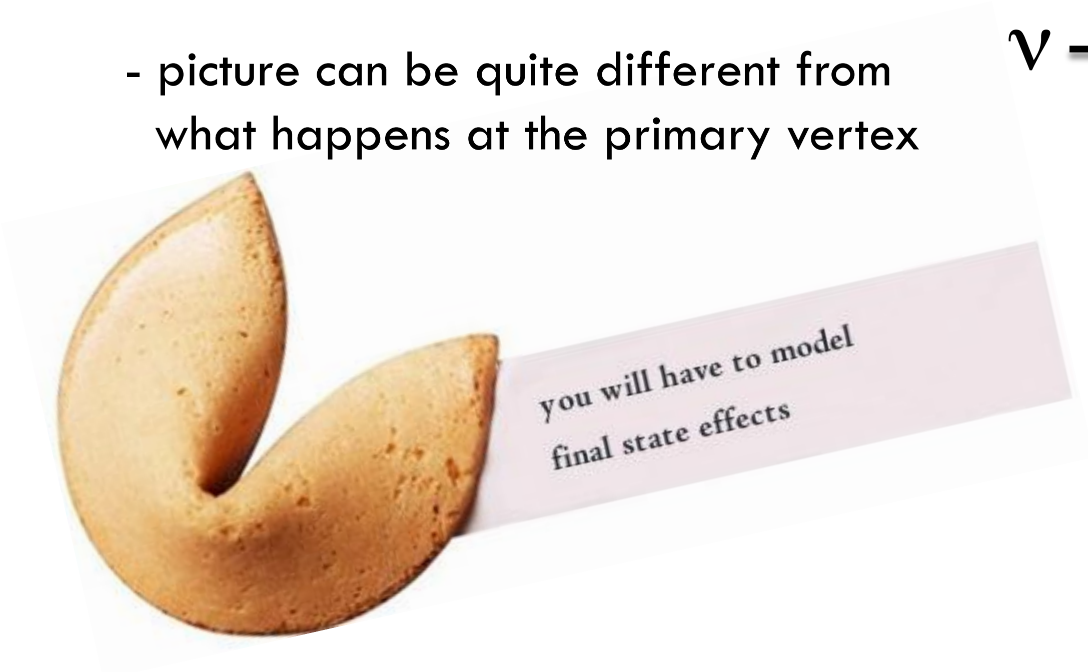

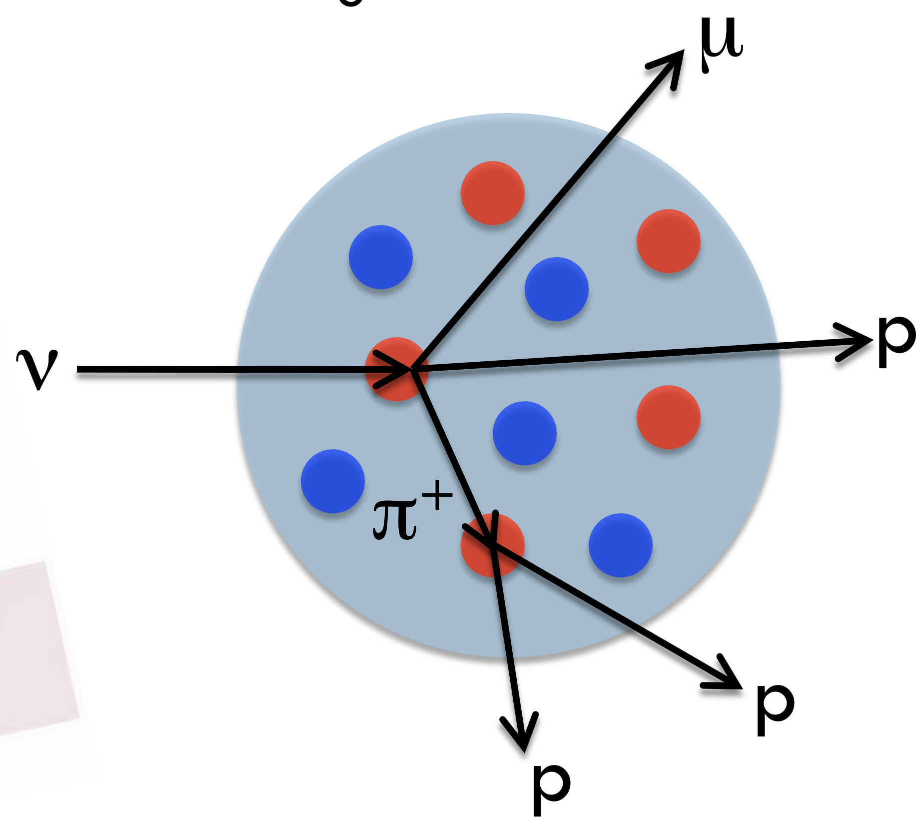

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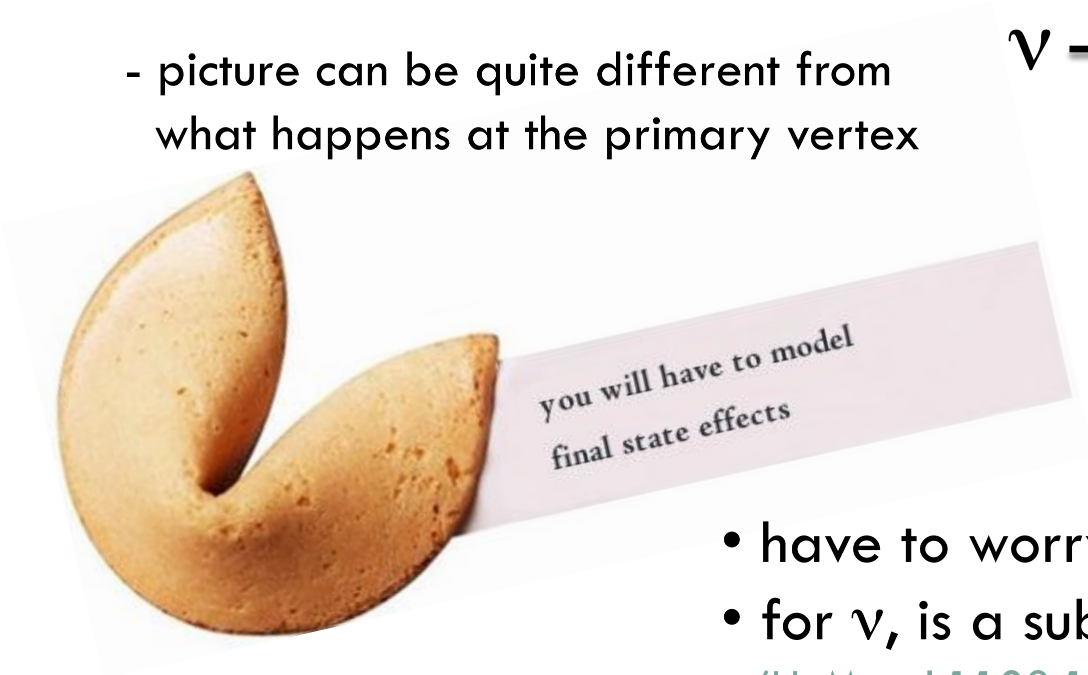
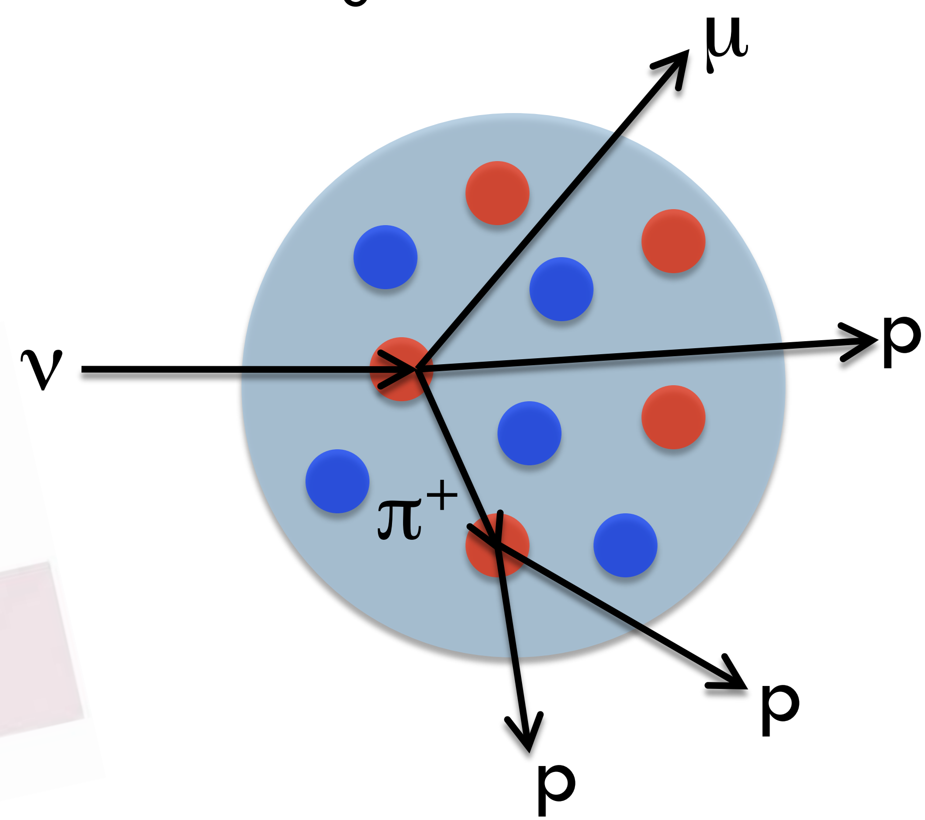




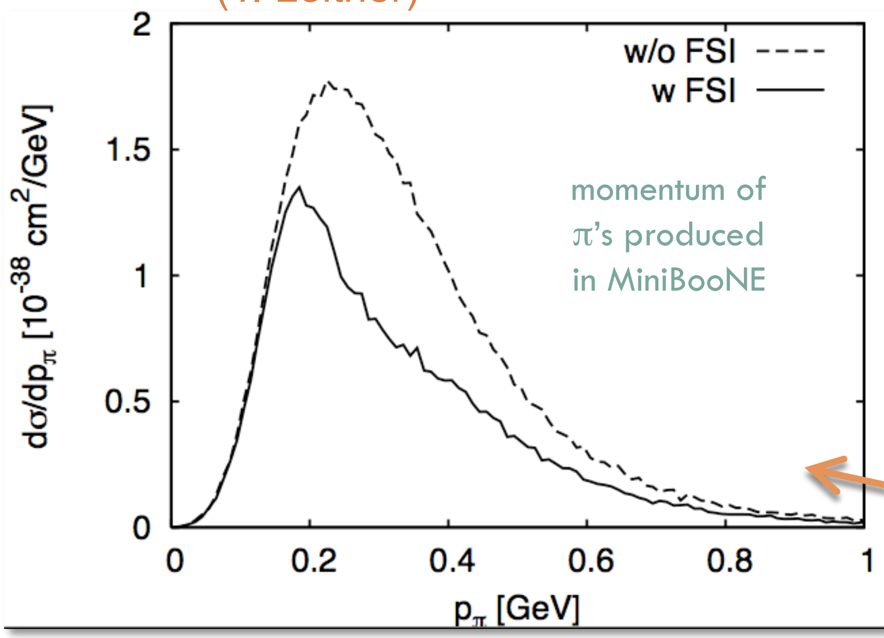
- have to worry about these effects
- for ν, is a subject that needs more attention

(U. Mosel,1108.1692 [nucl-th])

Final State Effects are Important

- the distortions are large (>20%)

(T. Leitner)



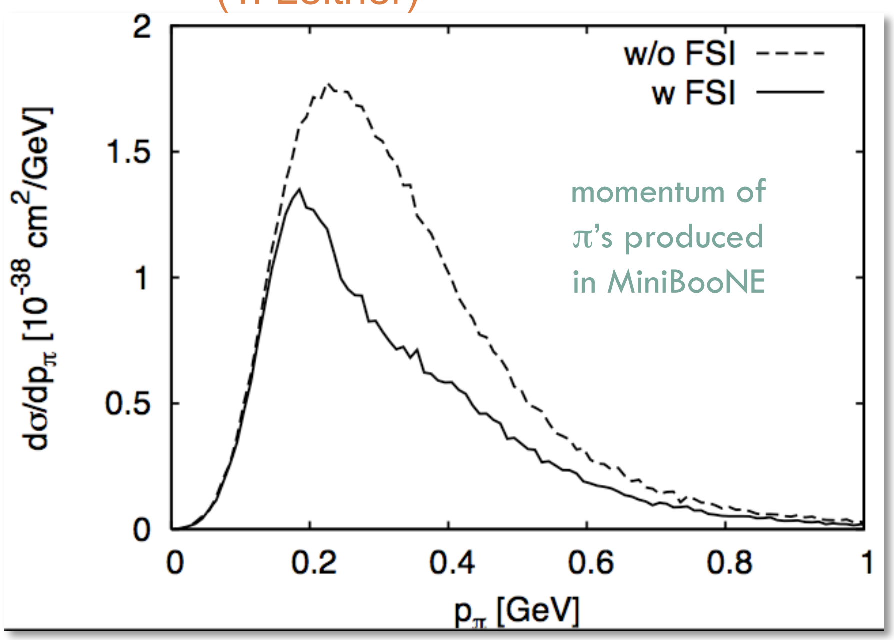
distribution that tends to be most effected by rescattering effects

- leaves a big imprint on what you see in your detector

Final State Effects are Important

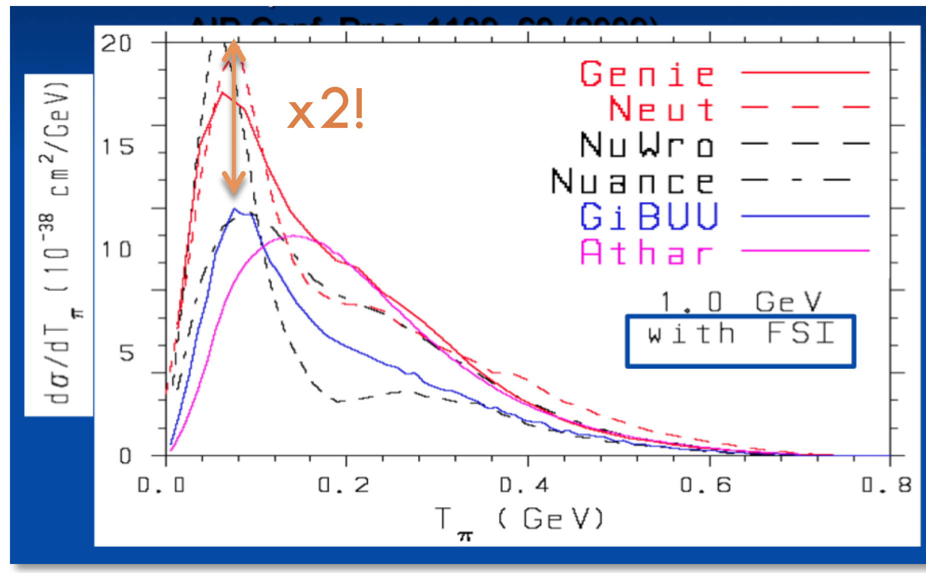
- the distortions are large (>20%)

(T. Leitner)



- and the predictions of their effects can vary

http://regie2.phys.uregina.ca/neutrino/



- leaves a big imprint on what you see in your detector

- area where generators differ the most
- need π kinematic measurements!

(has never been carefully studied in ν scattering)

π Production in MiniBooNE

- trying to forge a new path here also
- extensive program to measure final state particle kinematics

(after all of the nuclear effects have taken place)

Phys. Rev. **D81**, 013005 (2010)
Phys. Rev. **D83**, 052009 (2011)
Phys. Rev. **D83**, 052007 (2011)

score card:

"standard" cross section

the rest is new!

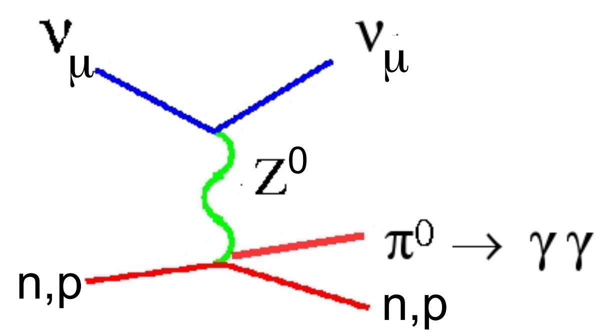
measurement	NC π^0	CC π^0	CC π^+
$\sigma(E_\nu)$	X	X	X
$d\sigma/dQ^2$		X	X
$d\sigma/dp_\pi$	X	X	X
$d\sigma/d\cos\theta_\pi$	X	X	X
$d\sigma/dT_\mu$		X	X
$d\sigma/d\cos\theta_\mu$		X	X
$d^2\sigma/dT_\mu d\cos\theta_\mu$			X
$d^2\sigma/dT_\pi d\cos\theta_\pi$			X

- absolute σ's for 3 channels, 14 diff'l σ's
- all of this data available online

http://www-boone.fnal.gov/for_physicists/data_release/

NC π^0 Production

Why important?

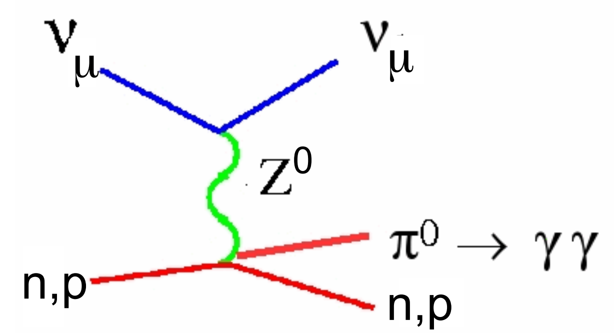


- **important for neutrino oscillation experiments**
  - very important background for experiments looking for $\nu_\mu \rightarrow \nu_e$ (θ_{13}, MH, ~~CP~~) final state can mimic a ν_e interaction if $\pi^0 \rightarrow \gamma\cancel{\gamma}$

background for oscillation experiments

NC π^0 Production

Why important?



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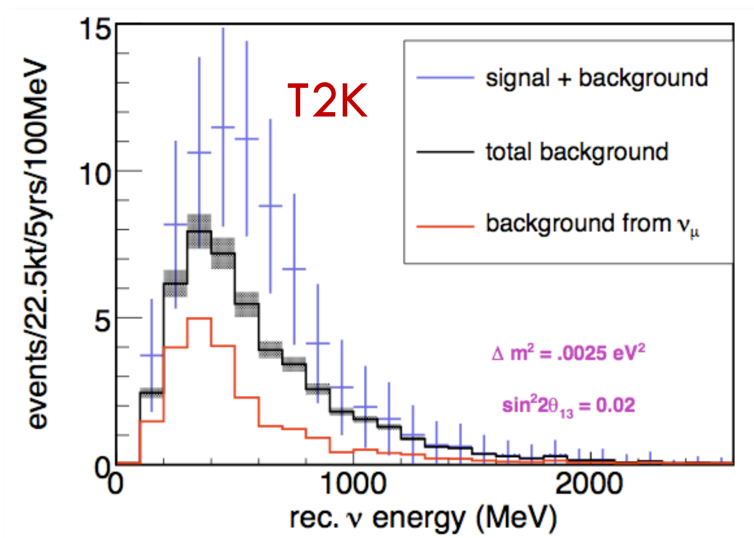
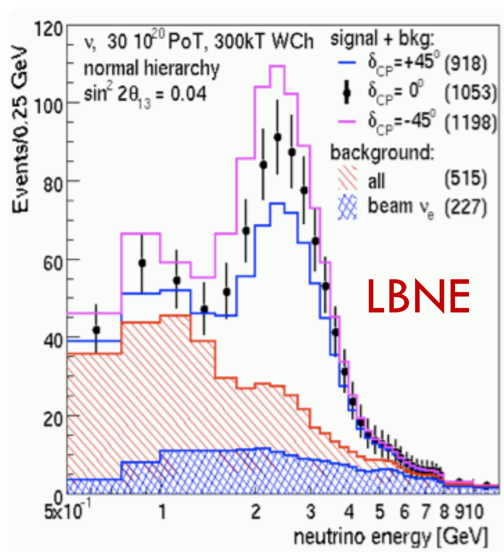




can be a sizable background

goal:
5-10%
level or better

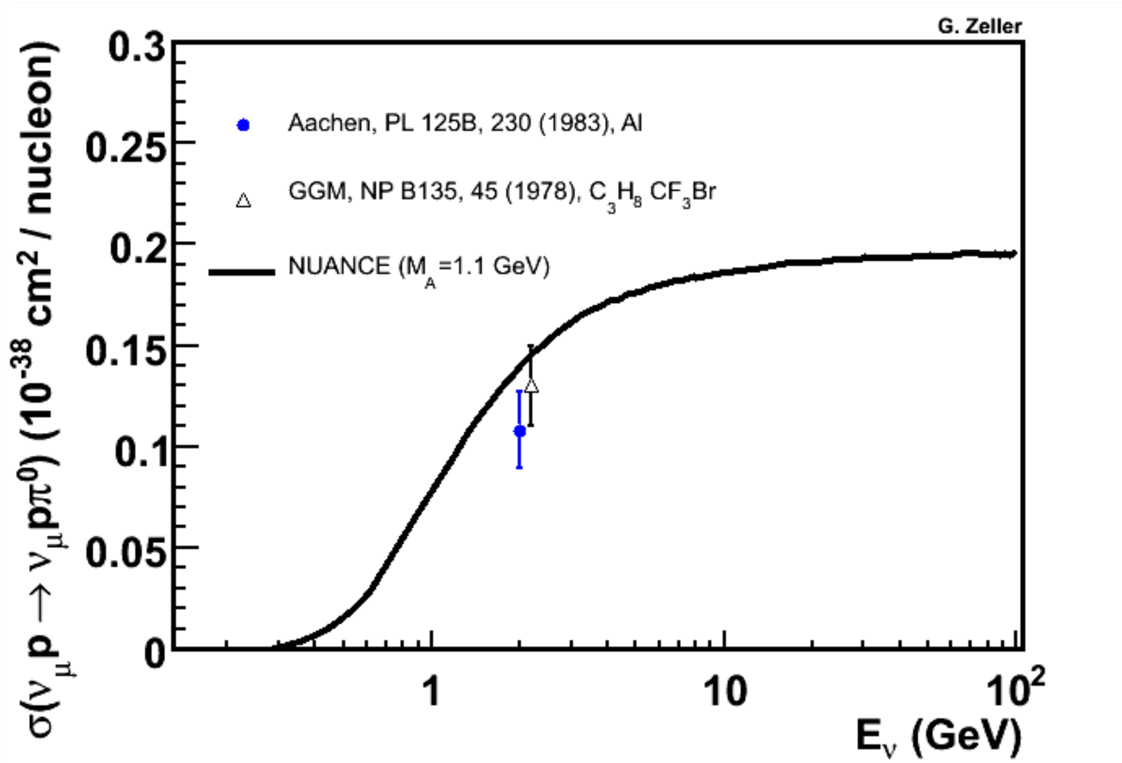
Historically …

- interesting to go back through some of the history here too ….

- only two pre-existing NC π^0 σ measurements (1978, 1983)

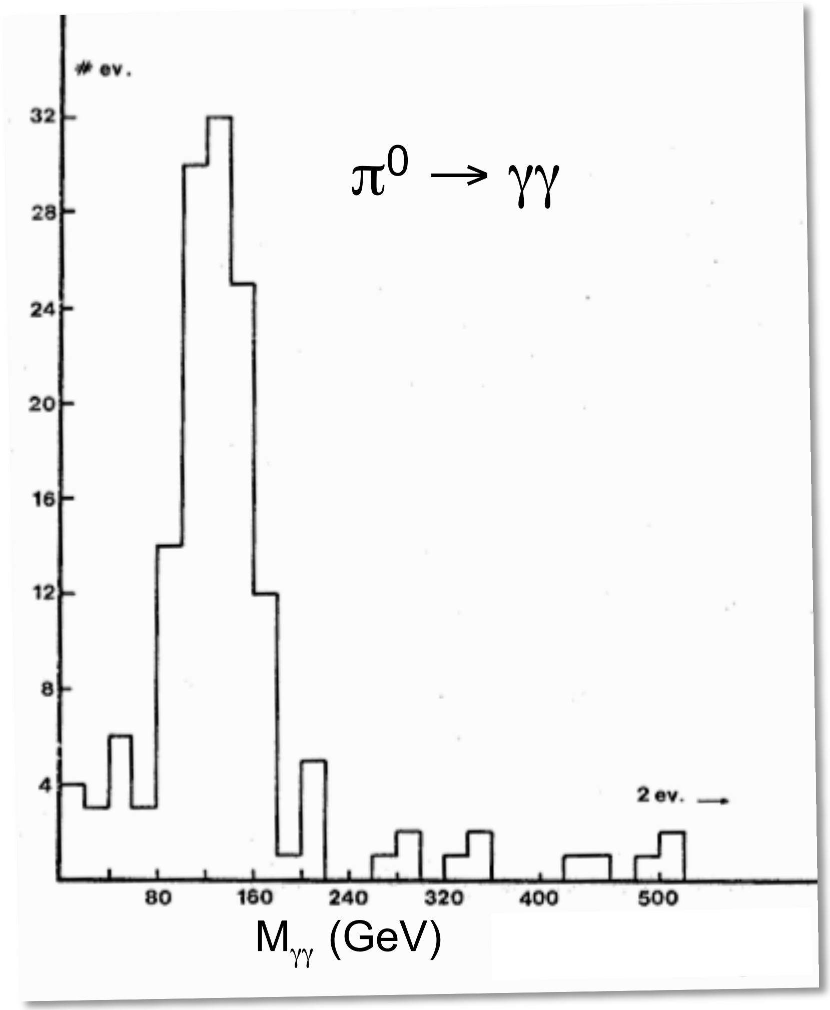
- both at ~2 GeV

- <u>historically:</u>
  - *$\sigma(E_\nu)$ at a single E_ν point*
  - *at the time, interest in studying neutral currents, not in understanding this as an oscillation bkg*



Historically ...

Krenz *et al.*, Nucl. Phys. **B135**, 45 (1978)

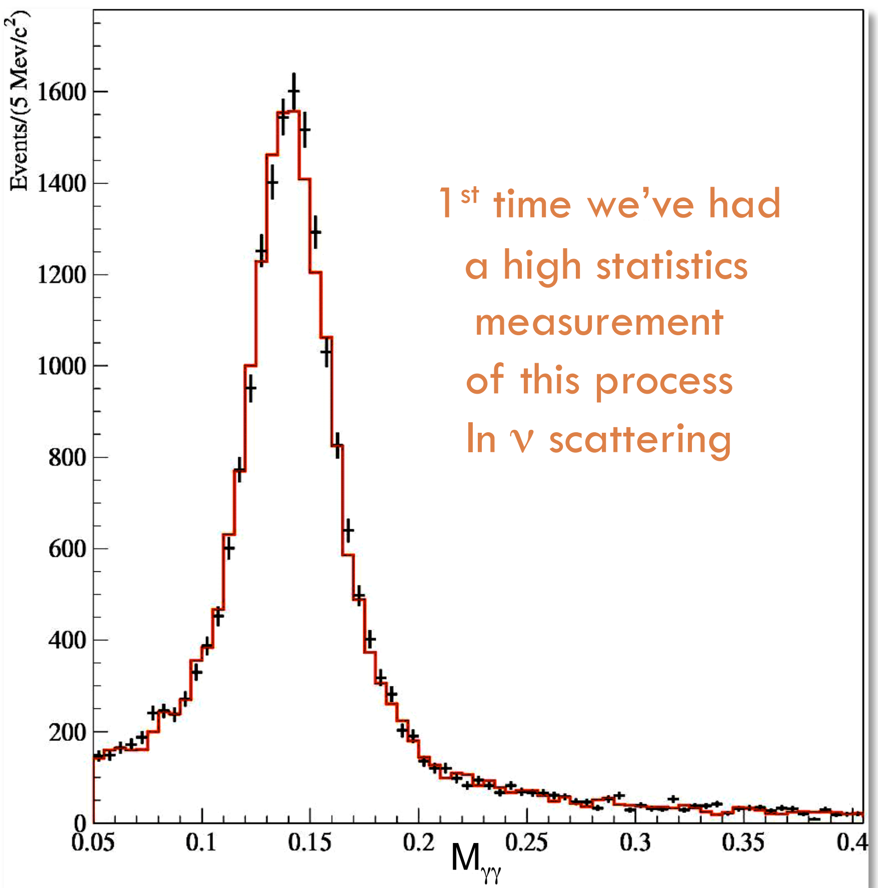


- 240 NC π^0 events
- Gargamelle bubble chamber, propane-freon

this is what oscillation exps have initially known about their NC π^0 backgrounds going in

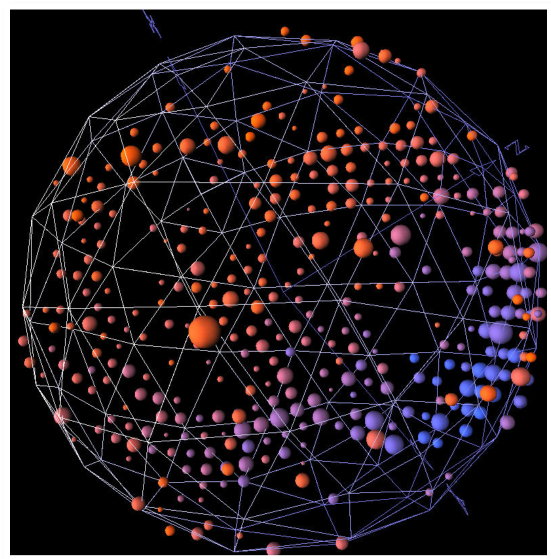
NC π^0 at MiniBooNE

- coming back to this 30 years later …



- 21,542 ν_μ NC π^0 events
- 2,305 $\overline{\nu_\mu}$ NC π^0 events

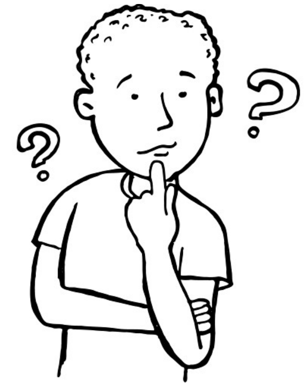
~100x more data than previously available!



$\pi^0 \rightarrow \gamma\gamma$

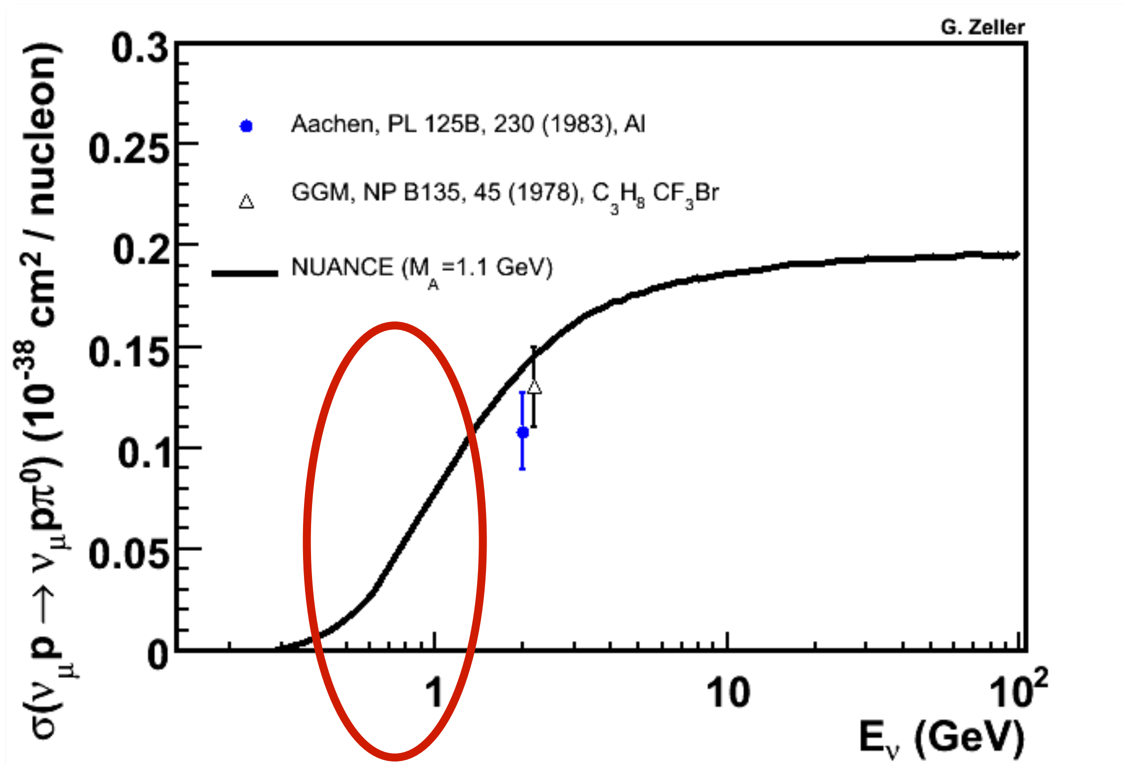
R.B. Patterson *et al.*, NIM **A608**, 206 (2009)

Constraining NC π^0 Backgrounds



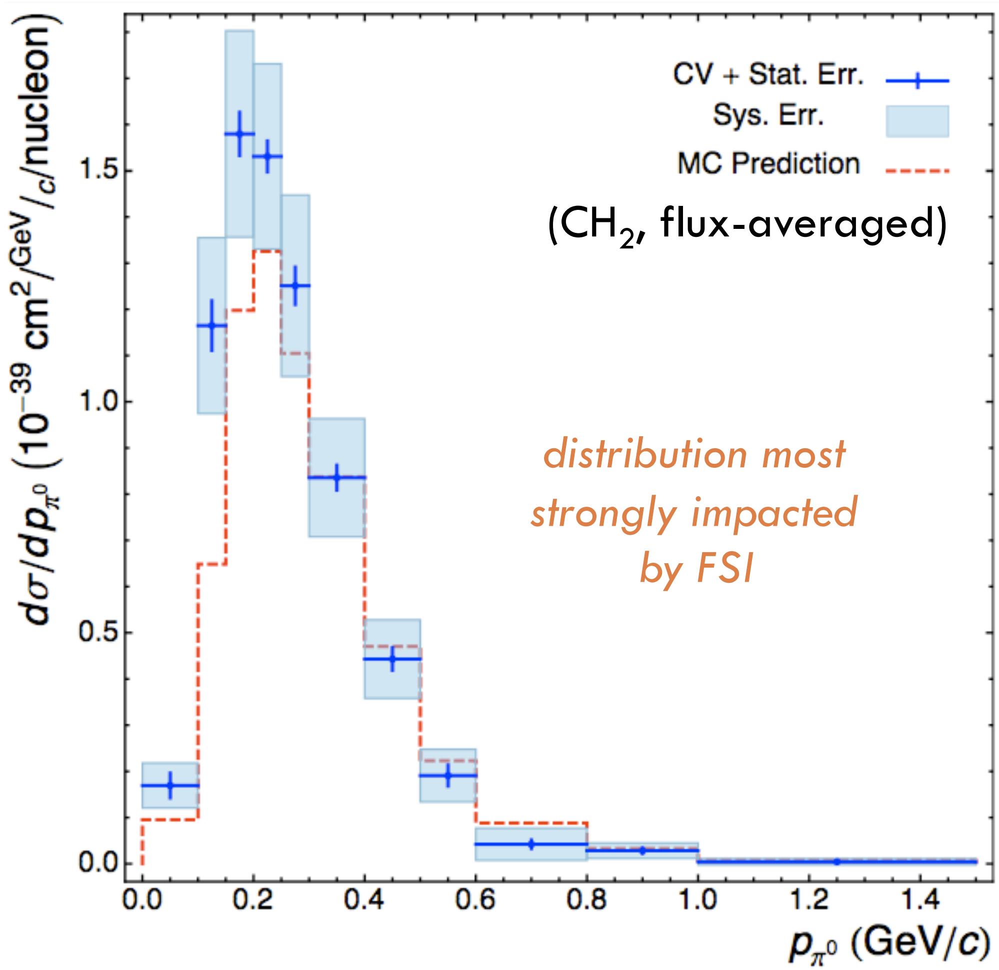
- one thing we realized in going through the mechanics of the $\nu_\mu \rightarrow \nu_e$ analysis in MiniBooNE and looking for sub-1% signal, is that it's not just an issue of adding another data point to this plot

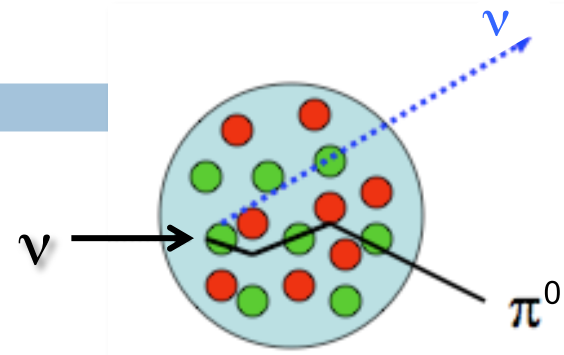
- from MB experience, we quickly realized that this was not good enough! this will also be true for experiments like T2K, NOvA, LBNE



NC π^0 at MiniBooNE

Aguilar-Arevalo *et al.*, PRD **81**, 013005 (2010)





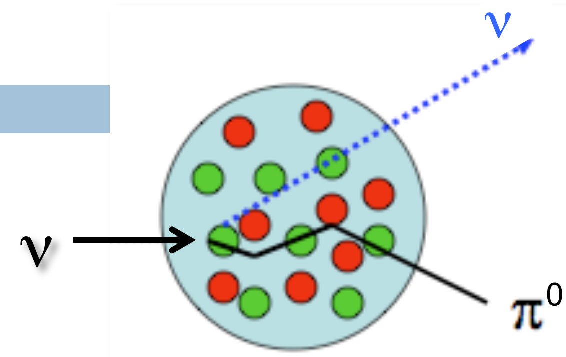
- one of our flagship meas
- what this is is the total σ for a NC interaction to produce π^0 exiting the target nucleus

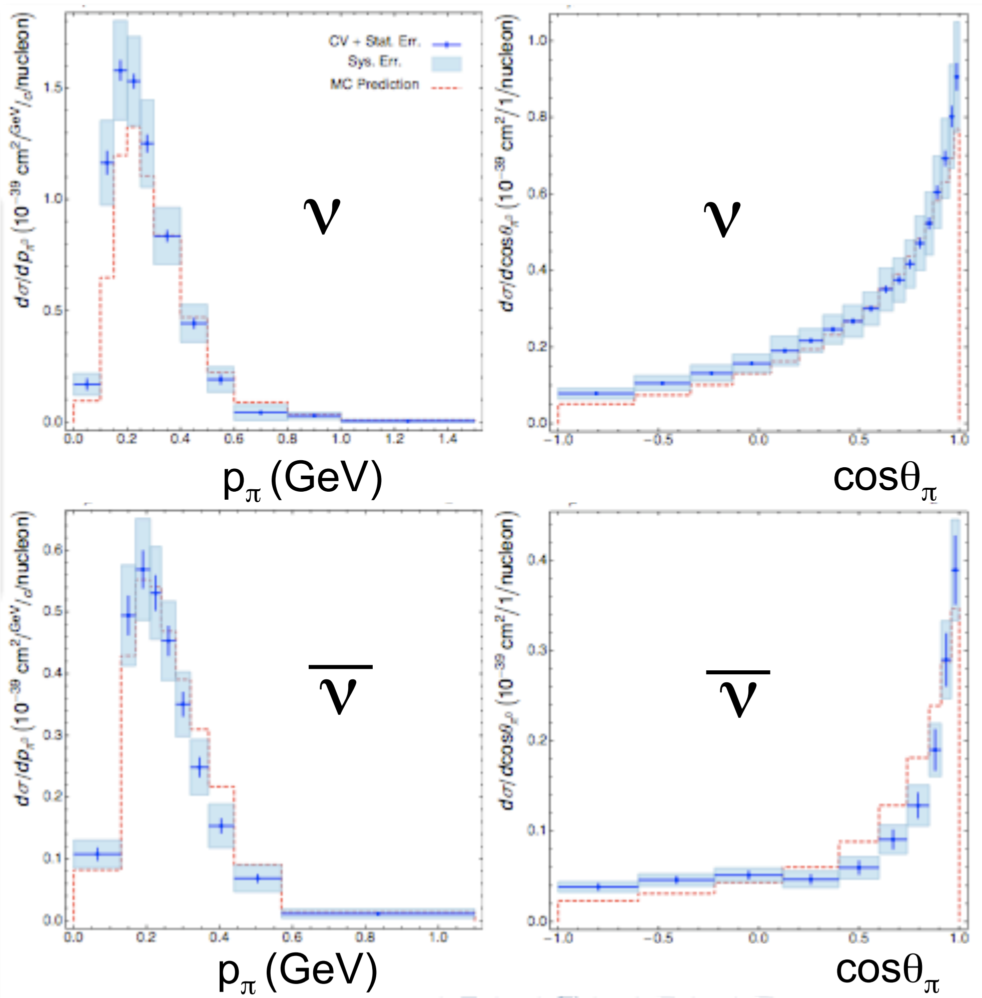
  (this is what we care about, "observed cross section")
- have <u>not</u> corrected back to primary interaction vertex

  (this is something new!)

NC π^0 at MiniBooNE

Aguilar-Arevalo *et al.*, PRD **81**, 013005 (2010)



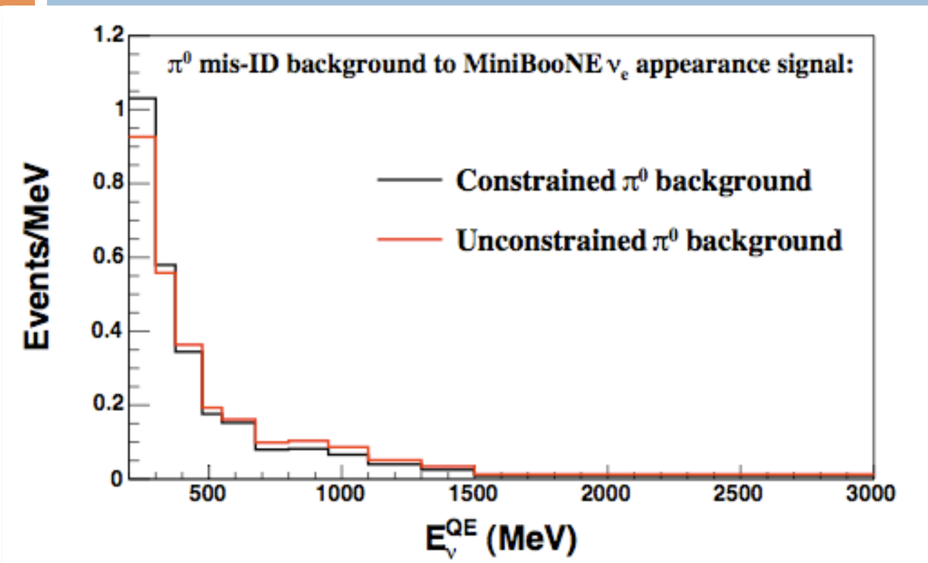


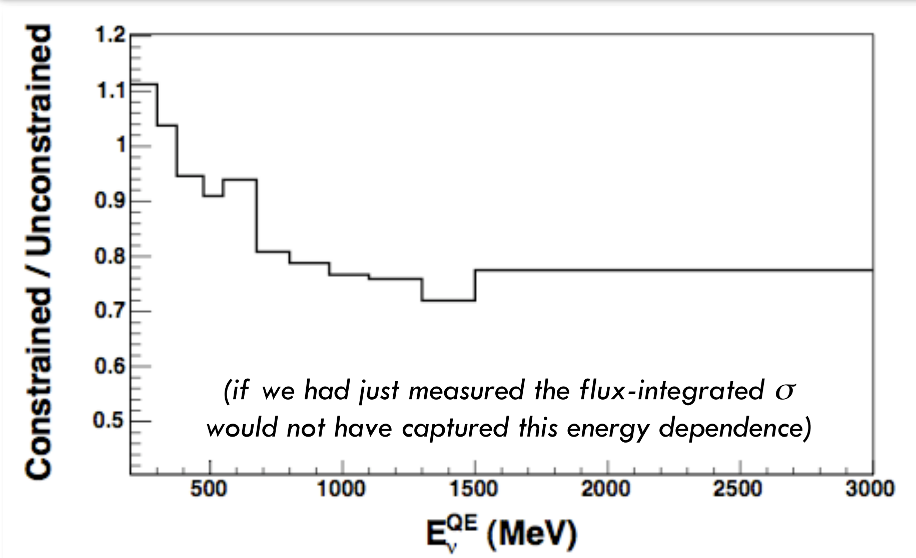
(CH$_2$, *flux-averaged)*

- this is the 1st time differential σ's have been provided for such neutrino interactions

C. Anderson, Yale, Ph.D. thesis

NC π^0 at MiniBooNE





(G. Karagiorgi, MIT)

- this data crucial for MB $\nu_\mu \rightarrow \nu_e$ oscillation search

  (dominant ν_μ-induced bkg to ν_e app search)

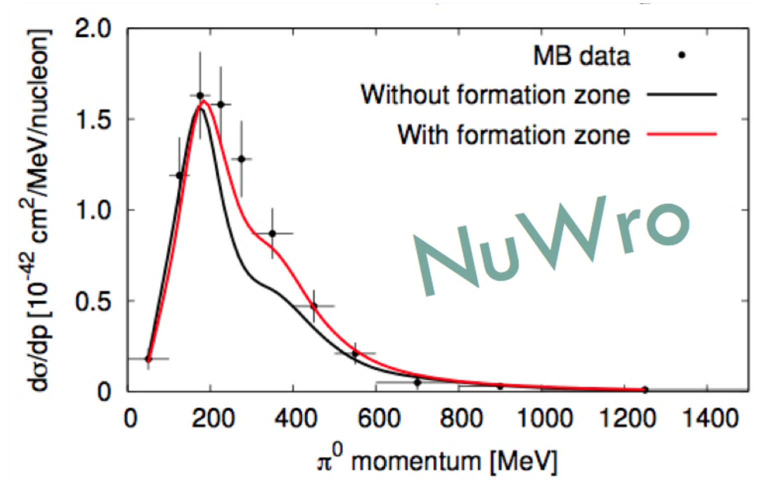
uncertainty in NC π^0 backgrounds reduced by a factor of 5

(full kinematic constraint)

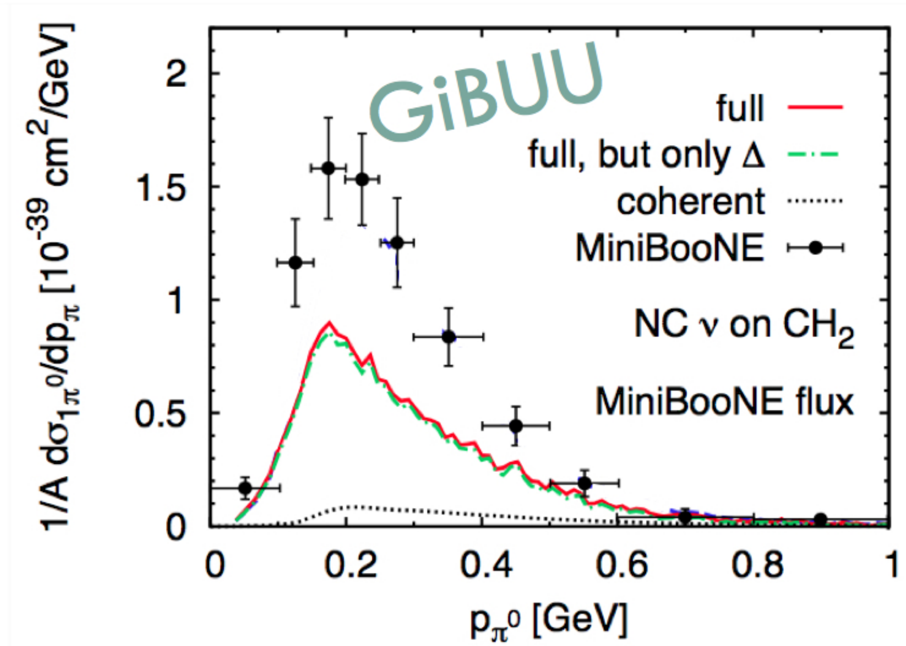
- by providing diff'l σ's, the data is now in a form others can use

Transport Models

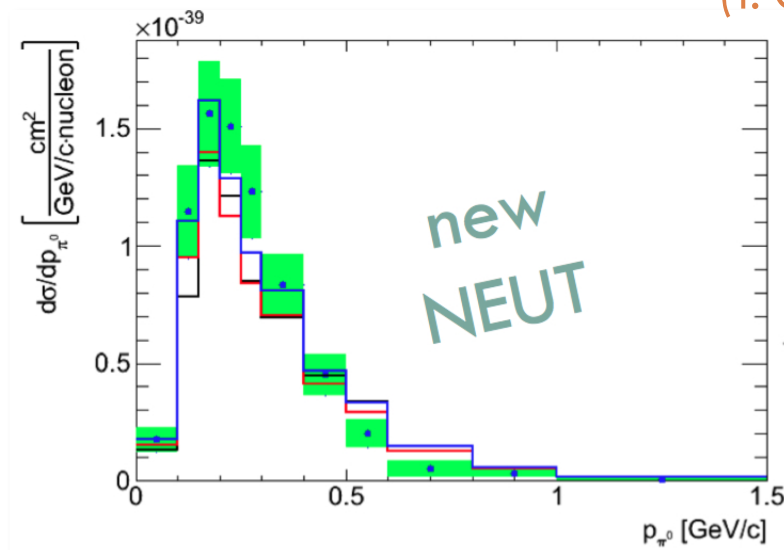
- MiniBooNE π production data has been in heavy use by FSI model builders (and T2K)



(T. Golan)



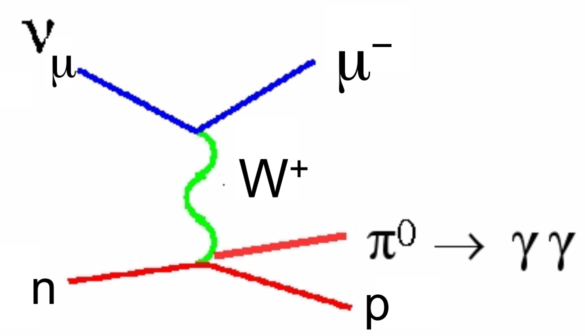
(U. Mosel)

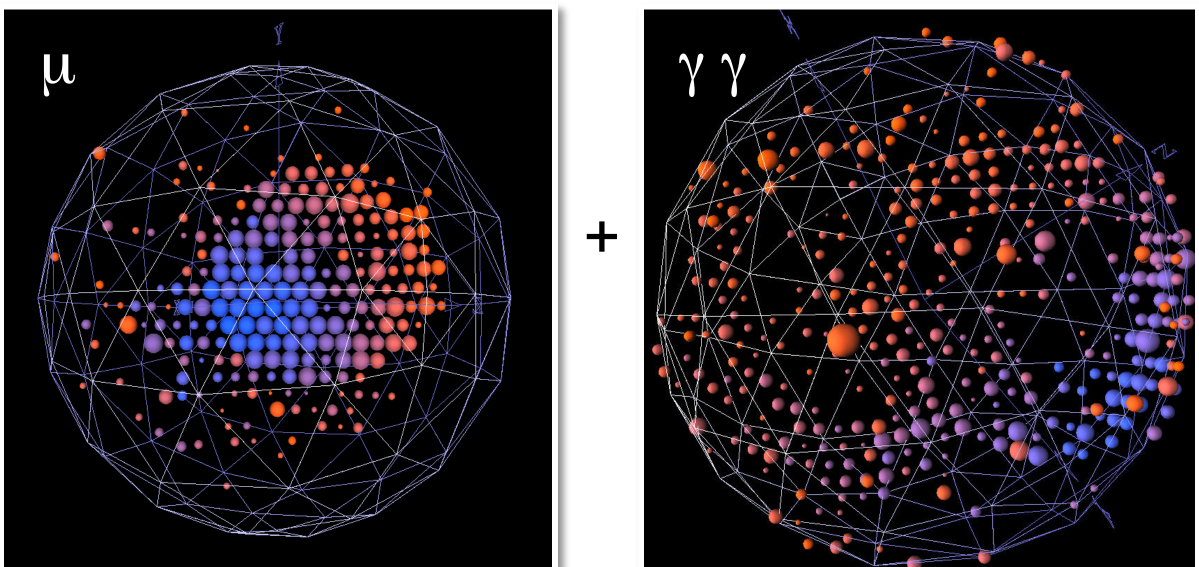


(P. dePerio)

CC π^0 at MiniBooNE

- as a cross-check, also decided to look at CC equivalent of this process
- these events have 3 Čerenkov rings, so developed a custom 3-ring fitter
  (B. Nelson, UC Boulder, Ph.D. thesis)
- most complex final state that attempt to reconstruct in MiniBooNE



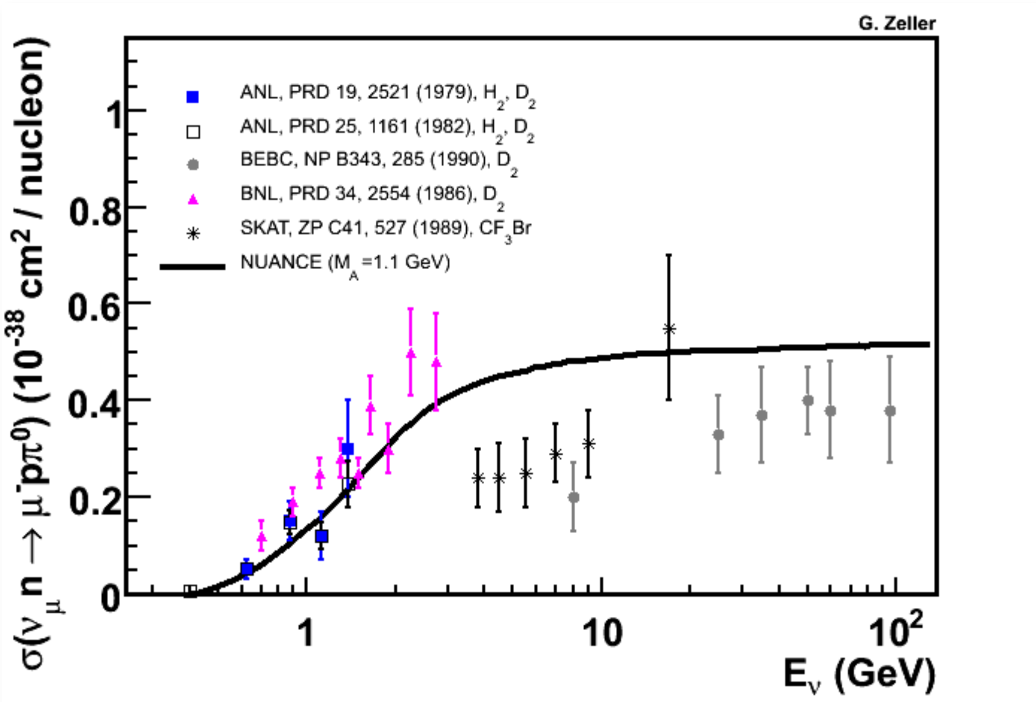


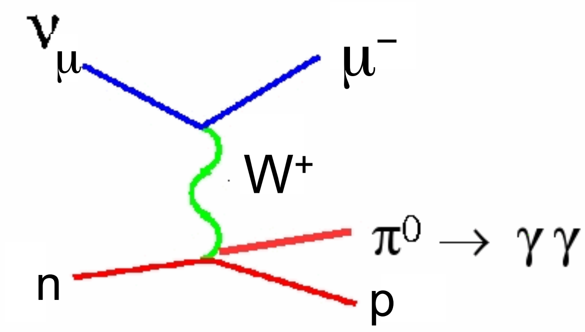
= 3 ring mess

- 5,800 events
  (>3x all previous data combined)

Historic CC π^0 Measurements

- this is what we've known on this reaction





- most of the focus was on measuring $\sigma(E_\nu)$
- models tend to underpredict the cross section at low E_ν
- x2 difference between some of the measurements

… this is our starting point

CC π^0 at MiniBooNE

Measurement of ν_μ-induced charged-current neutral pion production cross sections on mineral oil at $E_\nu \in 0.5 - 2.0$ GeV

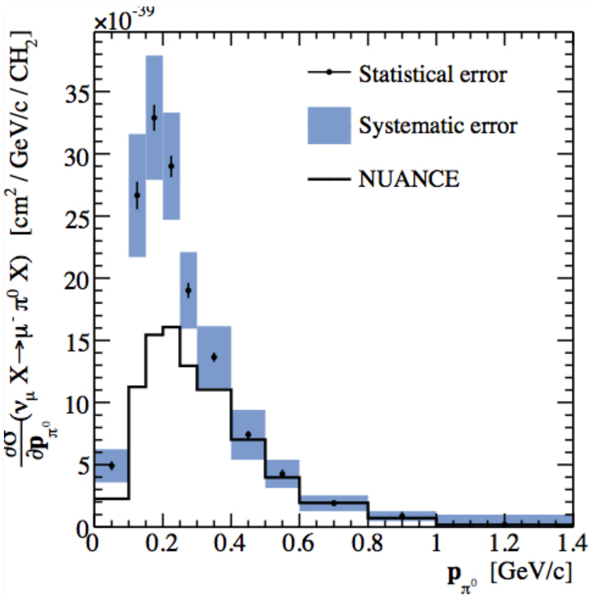
A. A. Aguilar-Arevalo,[14] C. E. Anderson,[19] A. O. Bazarko,[16] S. J. Brice,[8] B. C. Brown,[8] L. Bugel,[13] J. Cao,[15] L. Coney,[6] J. M. Conrad,[13] D. C. Cox,[10] A. Curioni,[19] R. Dharmapalan,[1] Z. Djurcic,[2] D. A. Finley,[8] B. T. Fleming,[19] R. Ford,[8] F. G. Garcia,[8] G. T. Garvey,[11] J. Grange,[9] C. Green,[8,11] J. A. Green,[10,11] T. L. Hart,[5] E. Hawker,[4,11] R. Imlay,[12] R. A. Johnson,[4] G. Karagiorgi,[13] P. Kasper,[8] T. Katori,[10,13] T. Kobilarcik,[8] I. Kourbanis,[8] S. Koutsoliotas,[3] E. M. Laird,[16] S. K. Linden,[19] J. M. Link,[18] Y. Liu,[15] Y. Liu,[1] W. C. Louis,[11] K. B. M. Mahn,[6] W. Marsh,[8] C. Mauger,[11] V. T. McGary,[13] G. McGregor,[11] W. Metcalf,[12] P. D. Meyers,[16] F. Mills,[8] G. B. Mills,[11] J. Monroe,[6] C. D. Moore,[8] J. Mousseau,[9] R. H. Nelson,[5,*] P. Nienaber,[17] J. A. Nowak,[12] B. Osmanov,[9] S. Ouedraogo,[12] R. B. Patterson,[16] Z. Pavlovic,[11] D. Perevalov,[1,8] C. C. Polly,[8] E. Prebys,[8] J. L. Raaf,[4] H. Ray,[9] B. P. Roe,[15] A. D. Russell,[8] V. Sandberg,[11] R. Schirato,[11] D. Schmitz,[8] M. H. Shaevitz,[6] F. C. Shoemaker,[16,†] D. Smith,[7] M. Soderberg,[19] M. Sorel,[6,‡] P. Spentzouris,[8] J. Spitz,[19] I. Stancu,[1] R. J. Stefanski,[8] M. Sung,[12] H. A. Tanaka,[16] R. Tayloe,[10] M. Tzanov,[5] R. G. Van de Water,[11] M. O. Wascko,[12,§] D. H. White,[11] M. J. Wilking,[5] H. J. Yang,[15] G. P. Zeller,[8] and E. D. Zimmerman[5]

(MiniBooNE Collaboration)

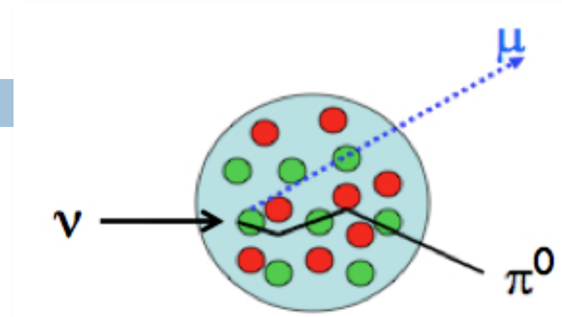
[1] *University of Alabama; Tuscaloosa, AL 35487*
[2] *Argonne National Laboratory; Argonne, IL 60439*
[3] *Bucknell University; Lewisburg, PA 17837*
[4] *University of Cincinnati; Cincinnati, OH 45221*
[5] *University of Colorado; Boulder, CO 80309*
[6] *Columbia University; New York, NY 10027*
[7] *Embry-Riddle Aeronautical University; Prescott, AZ 86301*
[8] *Fermi National Accelerator Laboratory; Batavia, IL 60510*
[9] *University of Florida; Gainesville, FL 32611*
[10] *Indiana University; Bloomington, IN 47405*
[11] *Los Alamos National Laboratory; Los Alamos, NM 87545*
[12] *Louisiana State University; Baton Rouge, LA 70803*
[13] *Massachusetts Institute of Technology; Cambridge, MA 02139*
[14] *Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México, D.F. 04510, México*
[15] *University of Michigan; Ann Arbor, MI 48109*
[16] *Princeton University; Princeton, NJ 08544*
[17] *Saint Mary's University of Minnesota; Winona, MN 55987*
[18] *Virginia Polytechnic Institute & State University; Blacksburg, VA 24061*
[19] *Yale University; New Haven, CT 06520*

(Dated: December 28, 2010)

Using a custom 3 Čerenkov-ring fitter, we report cross sections for ν_μ-induced charged-current single π^0 production on mineral oil (CH_2) from a sample of 5810 candidate events with 57% signal purity over an energy range of 0.5 – 2.0 GeV. This includes measurements of the absolute total cross section as a function of neutrino energy, and flux-averaged differential cross sections measured in terms of Q^2, μ^- kinematics, and π^0 kinematics. The sample yields a flux-averaged total cross section of $(9.2 \pm 0.3_{stat.} \pm 1.5_{syst.}) \times 10^{-39}$ cm^2/CH_2 at mean neutrino energy of 0.965 GeV.



Aguilar-Arevalo, PRD **83**, 052009 (2011)



- have measured a variety of kinematics for this process:

  $\sigma(E_\nu)$, $d\sigma/dQ^2$

  $\left.\begin{array}{l} d\sigma/dT_\mu,\ d\sigma/d\theta_\mu \\ d\sigma/dp_\pi,\ d\sigma/d\theta_\pi \end{array}\right\}$ reduced model-independence

- most comprehensive study of CC π^0 to date (B. Nelson, UC Boulder, Ph.D. thesis)

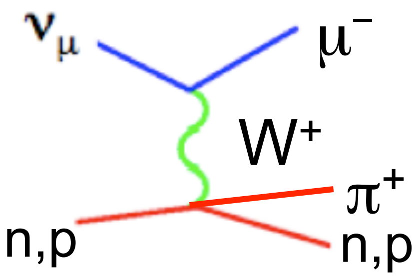
  - excess of data/model also present in this channel too
  - similar effects seen by K2K (higher E_ν)

    C. Mariani *et al.*, Phys. Rev. D83, 054023 (2011)

My Niece Asks …

what about
charged pions?

CC π^+ at MiniBooNE



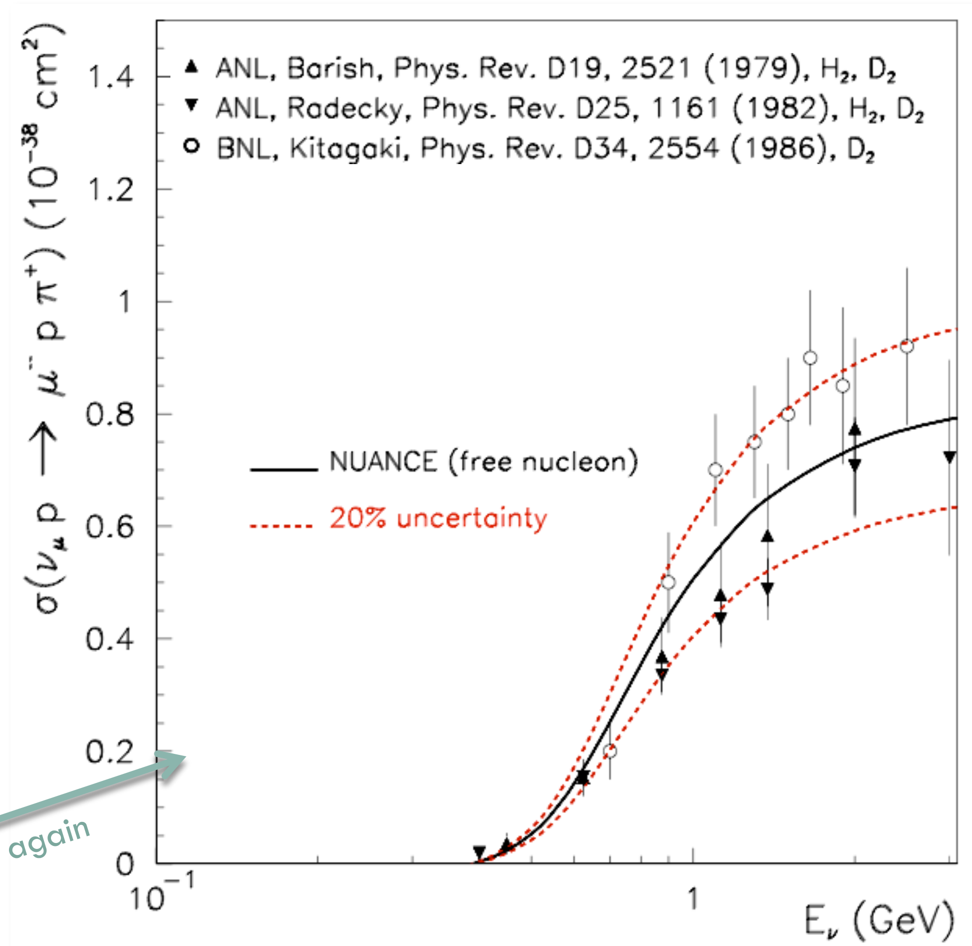
- important background for disappearance experiments

$$\nu_\mu \rightarrow \cancel{\nu}_\mu$$

- if π absorbed, impacts E_ν determination
- introduces a systematic on Δm^2_{23}, θ_{23}

- long-standing discrepancy between ANL & BNL (D_2)

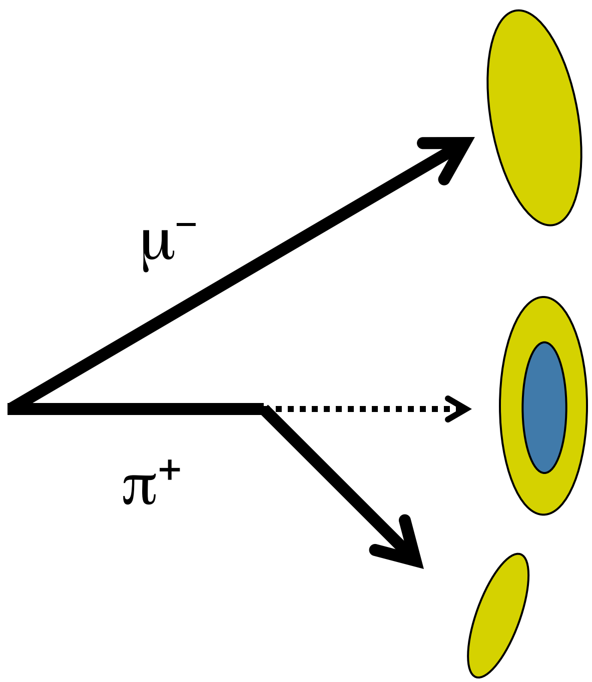
$\sigma(E_\nu)$ again



(didn't want to live with this for MB disapp)

CC π^+ at MiniBooNE

- want to measure more than $\sigma(E_\nu)$, but π^+ reconstruction in a Č detector and μ/π^+ separation are challenging - had never been done before



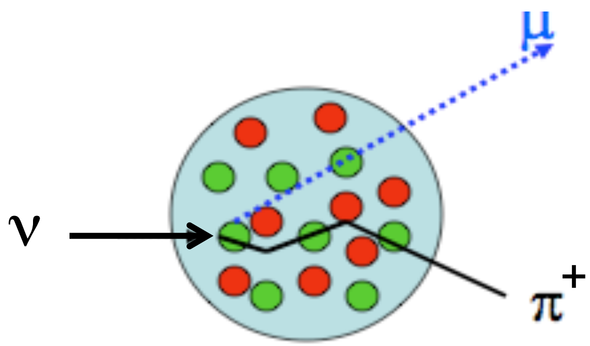
- π's frequently interact hadronically, losing energy & changing direction sharply
- kinked track produces two rings $\rightarrow$ kinked track fitter

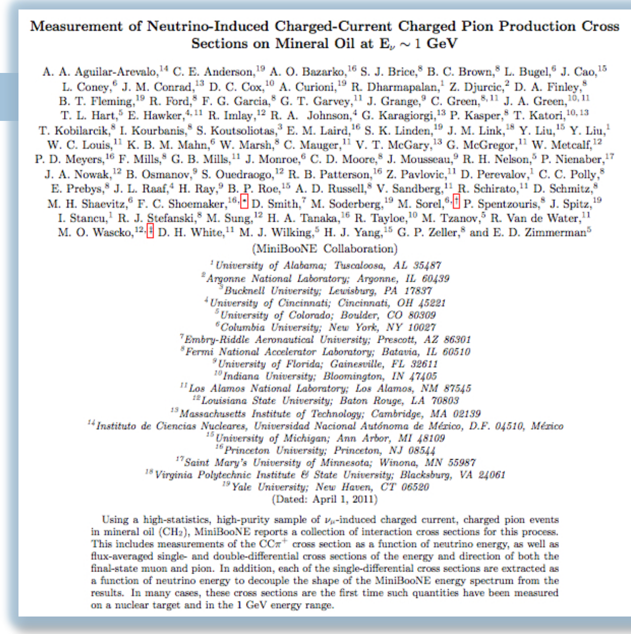
- algorithm developed to separately reconstruct muon & charged pion
  M. Wilking, UC Boulder, Ph.D. thesis
- 1st time has been done in a Č detector (correct ID 88% of the time)

CC π^+ at MiniBooNE

- highest purity sample (90% CC π^+)

  Aguilar-Arevalo *et al.*, PRD **83**, 052007 (2011)





Measurement of Neutrino-Induced Charged-Current Charged Pion Production Cross Sections on Mineral Oil at $E_\nu \sim 1$ GeV

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(MiniBooNE Collaboration)

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[5] *University of Colorado; Boulder, CO 80309*
[6] *Columbia University; New York, NY 10027*
[7] *Embry-Riddle Aeronautical University; Prescott, AZ 86301*
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[19] *Yale University; New Haven, CT 06520*

(Dated: April 1, 2011)

Using a high-statistics, high-purity sample of ν_μ-induced charged current, charged pion events in mineral oil (CH_2), MiniBooNE reports a collection of interaction cross sections for this process. This includes measurements of the CCπ^+ cross section as a function of neutrino energy, as well as flux-averaged single- and double-differential cross sections of the energy and direction of both the final-state muon and pion. In addition, each of the single-differential cross sections are extracted as a function of neutrino energy to decouple the shape of the MiniBooNE energy spectrum from the results. In many cases, these cross sections are the first time such quantities have been measured on a nuclear target and in the 1 GeV energy range.

- again, measuring complete final state kinematics

  (not correcting for nuclear effects … to ensure that the results are less model dependent)

$\sigma(E_\nu)$, $d\sigma/dQ^2$, $d^2\sigma/dT_\mu d\theta_\mu$,
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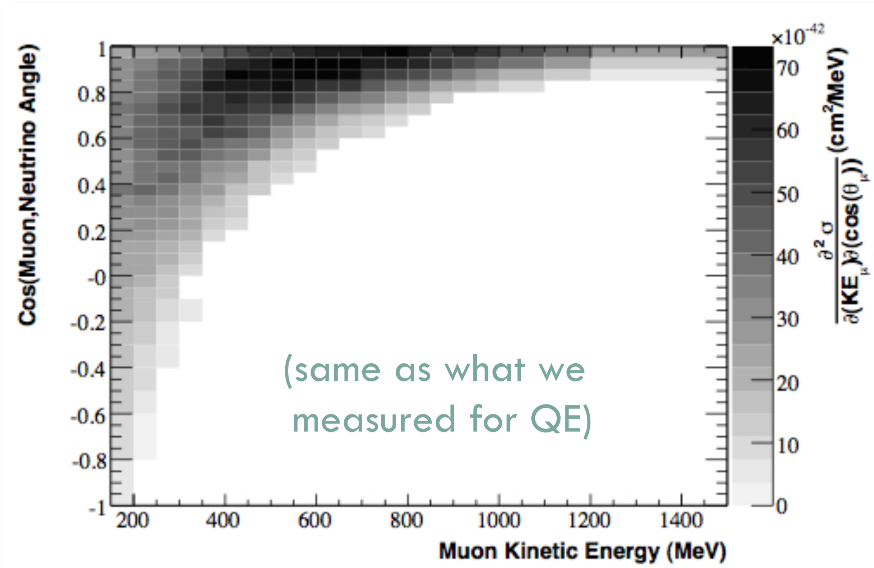
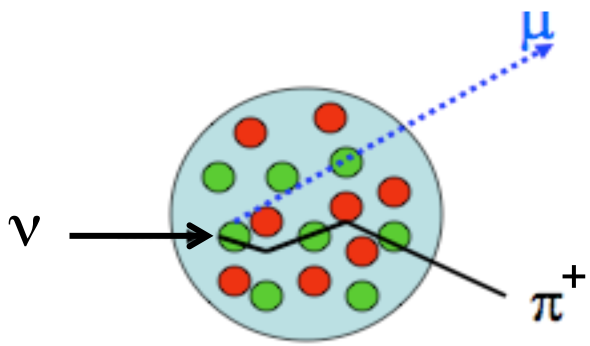
8 dists
(many firsts!)

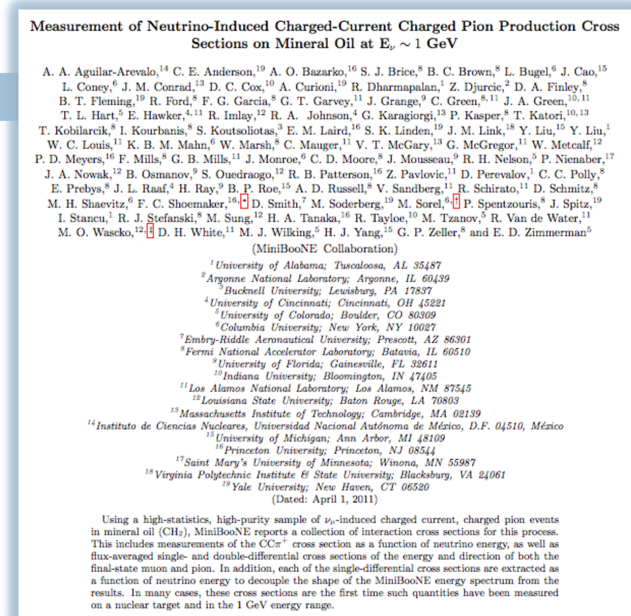


(same as what we measured for QE)

CC π^+ at MiniBooNE

- highest purity sample (90% CC π^+)
  Aguilar-Arevalo *et al.*, PRD **83**, 052007 (2011)





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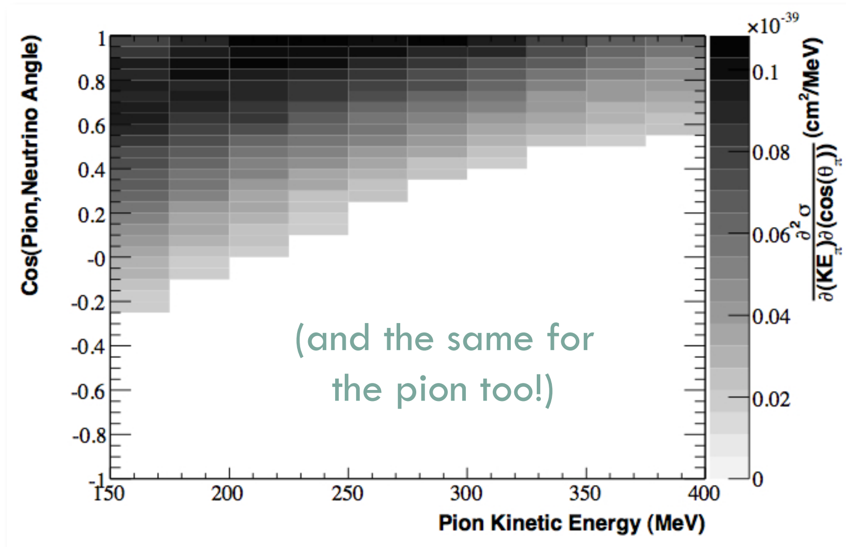
(many firsts!)



(and the same for the pion too!)

Future Prospects

- MB has provided a wealth of new ν scattering data; in this process, we have really thought about how to provide the most information possible

- coming soon: several antineutrino σ's and CC inclusive σ to wrap-up our program

- don't want to leave this open ended …

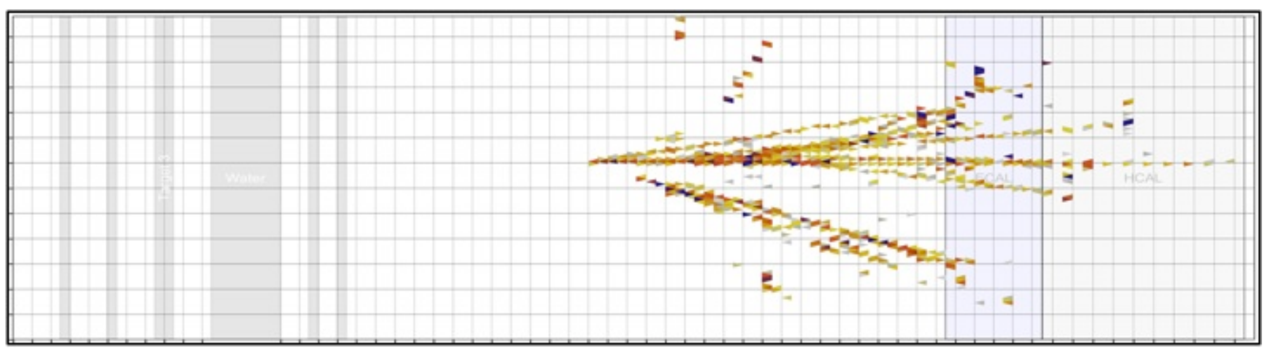
  - *having cross-checks, confirmation, and more information is very important!*

  - *what does the future hold? a lot of exps are getting into this business*

MINERνA

nuclear targets (He, C, Fe, Pb, H_2O, CH)

- **broad energy range** (1-20+ GeV)
  (will help close the gap between the low and high energy results with a single apparatus)
- **multiple nuclear targets** (He-Pb)
  (1st time this has been done; up to now much of the focus has been on O, C)
- starting data-taking with full detector in March 2010
- very large experimental program underway!

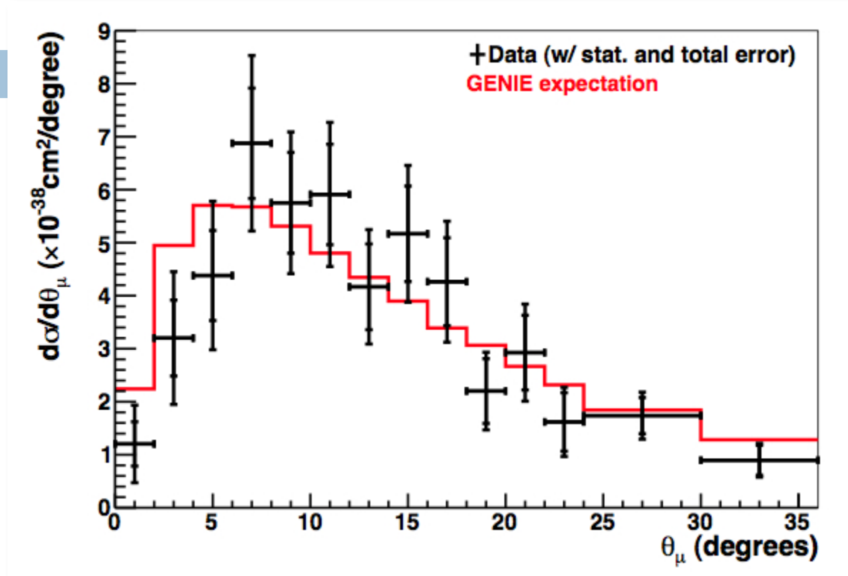


(example ν event in finely-segmented tracking detector) (D. Schmitz)

Liquid Argon TPCs

ArgoNeuT

- small TPC that took data in in NuMI beam (2009-2010)
- 1st publication
  arXiv:1111.0103, recently accepted by PRL



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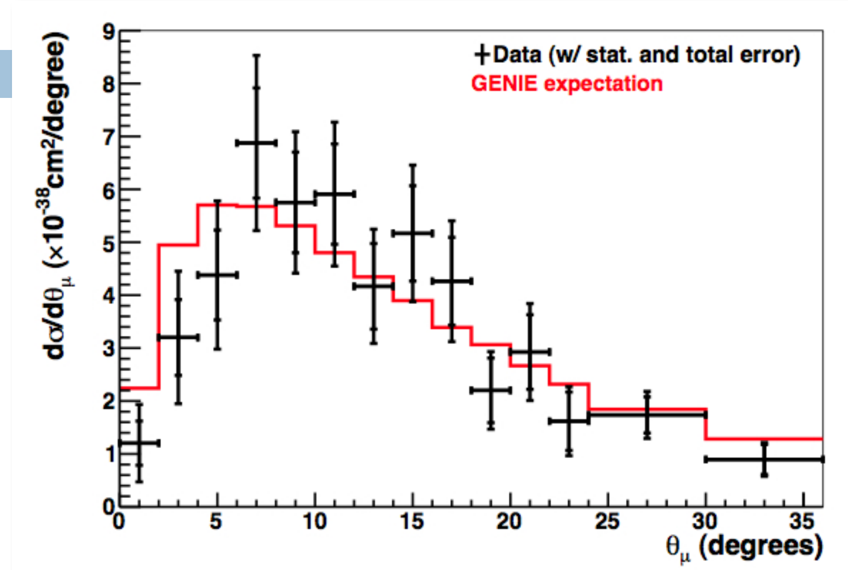


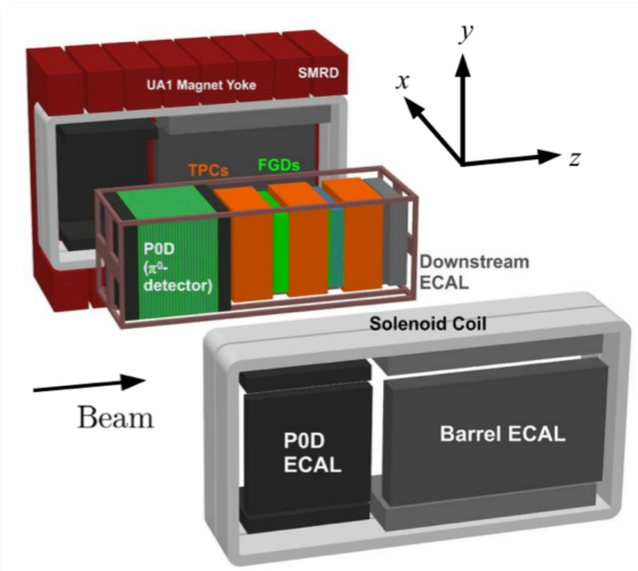
MicroBooNE

- 170 ton TPC in BNB beam
  (~600x size of ArgoNeuT)
- ground-breaking for detector hall in January
- data-taking in 2014

• will have σ_ν on Ar across a broad E range

Also, Near Detectors

(R. Tacik, NuInt 2011)

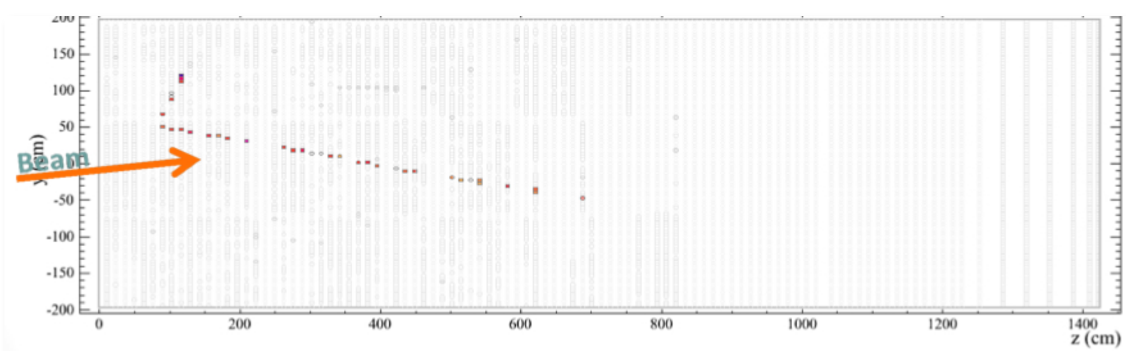


T2K ND

- near detector at 280m (ND280)
  - *very similar energy range as MiniBooNE*
  - *suite of fine-grained detector modules*

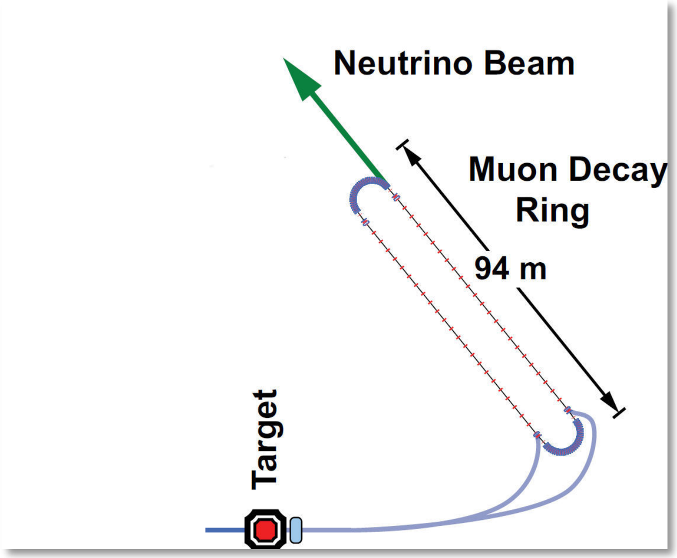
NOvA ND

- near detector on surface (NDOS) taking data now
  - *off-axis NuMI beam (NBB)*

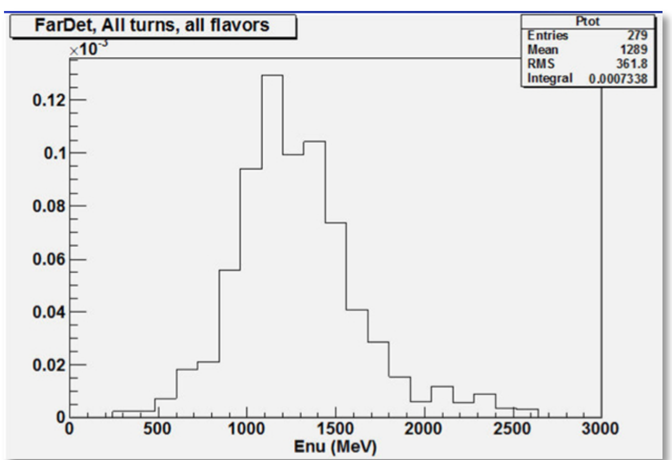


(J. Nowak, PANIC 2011)

New Ideas



(A. Bross, IF ν WG meeting 2011)



- knowledge of incoming ν flux has always been a limiting factor in these cross section measurements
- **very low energy neutrino factory (VLENF)**
- muon storage ring to produce large samples of $\mu^+ \rightarrow \nu_e, \overline{\nu}_\mu$ and $\mu^- \rightarrow \overline{\nu}_e, \nu_\mu$

goal: make the 1st measurements of ν_e and $\overline{\nu}_e$ cross sections at the few-% level in this energy range

Conclusions

- in the past couple years, there has been renewed appreciation for the complexities surrounding ν-nucleus scattering in the few-GeV region

- this has beeen a very active area of investigation in MiniBooNE
(9 publications, 5 channels, 24 differential σ distributions)

  - *probing nuclear effects with new precision*
  - *challenging assumptions about the size and source of nuclear effects at these energies*

- MiniBooNE σ_ν publications have garnered over 400 citations over the past year or more

- look forward to additional data

- crucial to have this physics under control for future ν oscillation investigations (MH, $\cancel{CP}$)

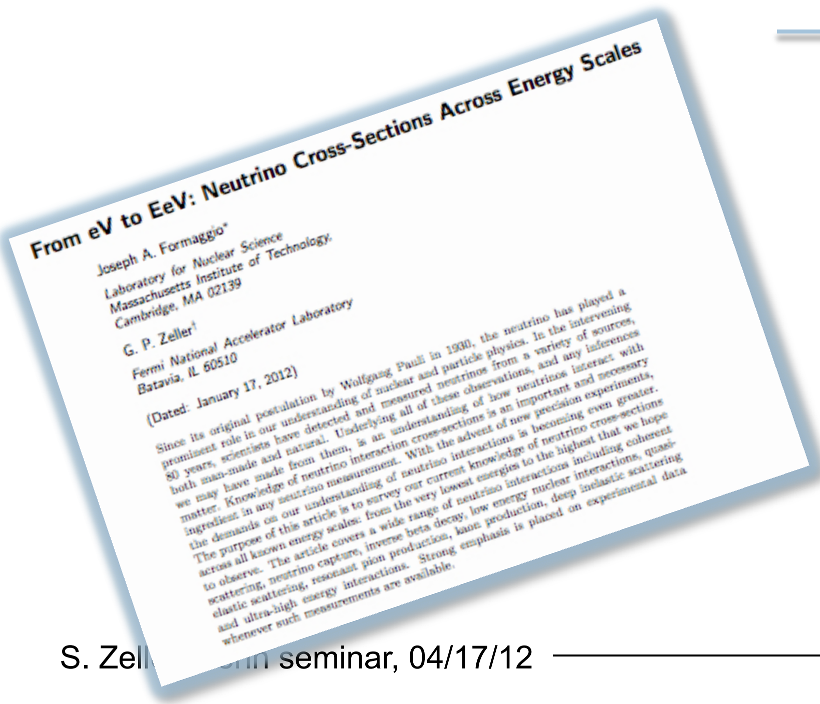
Further Reading

"Neutrino-Nucleus Interactions",
Ann. Rev. Nucl. Part. Sci. **61**, 355 (2011)
(H. Gallagher, G. Garvey, G.P. Zeller)

Neutrino-Nucleus Interactions

H. Gallagher,[1] G. Garvey,[2] and G.P. Zeller[3]

[1]Department of Physics, Tufts University, Medford, Massachusetts 02155; email: hugh.gallagher@tufts.edu
[2]Los Alamos National Laboratory, Los Alamos, New Mexico 87545; email: garvey@lanl.gov
[3]Fermi National Accelerator Laboratory, Batavia, Illinois 60510; email: gzeller@fnal.gov



From eV to EeV: Neutrino Cross-Sections Across Energy Scales

Joseph A. Formaggio*
Laboratory for Nuclear Science
Massachusetts Institute of Technology
Cambridge, MA 02139

G. P. Zeller†
Fermi National Accelerator Laboratory
Batavia, IL 60510

(Dated: January 17, 2012)

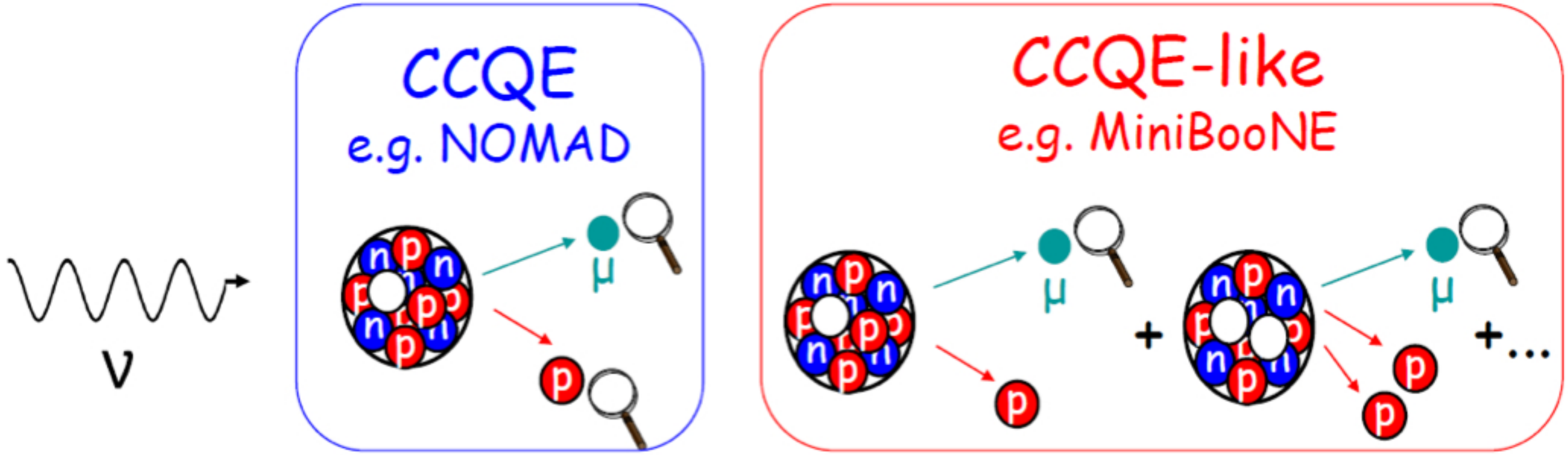
Since its original postulation by Wolfgang Pauli in 1930, the neutrino has played a prominent role in our understanding of nuclear and particle physics. In the intervening 80 years, scientists have detected and measured neutrinos from a variety of sources, both man-made and natural. Underlying all of these observations, and any inferences we may have made from them, is an understanding of how neutrinos interact with matter. Knowledge of neutrino interaction cross-sections is an important and necessary ingredient in any neutrino measurement. With the advent of new precision experiments, the demands on our understanding of neutrino interactions is becoming even greater. The purpose of this article is to survey our current knowledge of neutrino cross-sections across all known energy scales: from the very lowest energies to the highest that we hope to observe. The article covers a wide range of neutrino interactions including coherent scattering, neutrino capture, inverse beta decay, low energy nuclear interactions, quasi-elastic scattering, resonant pion production, kaon production, deep inelastic scattering and ultra-high energy interactions. Strong emphasis is placed on experimental data whenever such measurements are available.

"From eV to EeV: Neutrino Cross Sections Across Energy Scales",
Rev. Mod. Phys., to be published (2012)
(J. Formaggio, G.P. Zeller)

Thank you!

Backups

MiniBooNE/NOMAD QE Selection



μ+p

μ+p
μ+p+p